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Oberlin's Experimental Hazelnut Orchard: Exploring Woody Agriculture's Potential for Climate Change Mitigation and Food System Resilience

By: Naomi Fireman

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Chapter 1: Introduction

1.1 Contextualizing the issue

Continued human population growth and an increase in climate change induced disruptions are interrelated trends that present many challenges to humankind (Delgado et al. 2011). Central to these environmental challenges is the modern industrial agriculture system that has simultaneously allowed for a drastic increase in population and often times failed to provide adequate food, especially in developing countries (Crosson and Anderson 1994). It is likely that the global demand for food will double over the period 1990-2030, and maybe triple in the poorest countries (ibid). Modern industrial agriculture is not a sustainable system that can, over the long term, meet this demand; it is fundamentally dependent on non-renewable fossil fuel use, destroys habitats, decreases biodiversity, contributes to pollution and climate change, erodes soil, and consumes water resources that are being diminished in quantity and quality (Horrigan et al. 2002). Alternative forms of agriculture, such as woody crops, have been advocated for their potential to both address climate change and feed our growing population (Zalesny et al. 2016; Rutter 1989; Baah-Acheamfour et al. 2017; Wolz et al. 2017). Advocates argue that these forms of agriculture have higher capacity to produce food with less fossil fuel input and to sequester carbon in biomass and soil compared to conventional annual crops (Zalesny et al. 2016; Wolz et al. 2017). In this chapter I will explore the broader context of interconnected agriculture and population issues and how alternative forms of agriculture may be able to contribute to the solution. Subsequent chapters explain the biology of hazelnuts, the role of fertilizers in agroforestry systems, the methods used in this experiment, the results of eight years of data collection on an experimental hazelnut orchard at Oberlin College, the implications of this research, and how it contributes to the growing body of knowledge on woody agriculture.

Many environmental authorities argue that environmental challenges are caused in part by overpopulation and climate change; this endangers vulnerable communities (Bohle et al. 1994). Food insecurity is one of many serious issues we have faced for decades, along with contamination of waterways, overcrowding in cities, and non-renewable energy consumption. This type of energy consumption emits greenhouse gases and triggers atmospheric pollution and climate change (IPCC 2018). What are needed to address these broad, multi-dimensional challenges are synergistic, intersecting solutions (Stringer 2009).

Modern industrial agriculture that uses annual plants creates a multitude of environmental problems. To begin, habitat fragmentation and loss following the creation of agricultural fields cause loss of carbon storage potential, loss of biodiversity, pollution of water resources, and erosion of soils (Horrigan et al. 2002; Valenzuela 2016). Crops such as corn and soy are typically planted to be used not for direct human consumption, but for other massive industries that produce meat, biofuels, and highly processed food constituents. Accordingly, industrial farms use monocultures for large yields and growth efficiency; however, they require large quantities of fertilizer and pesticides to grow successfully. Nutrient loading of nitrogen and phosphorus-containing fertilizers from farms to aquatic ecosystems creates eutrophication, hypoxia, and dead zones in outflows of large rivers (Rabalais 2002). In addition, tilling and planting are required every single season when using annual crops, and this strips the soil of its nutrients and fertility (Rutter 1989). Pesticide-reliant agriculture that utilizes tilling negatively affects ground-nesting and social bee species (Williams et al. 2010) and other important insects. As human population grows and climate change continues to augment environmental problems, different agroecosystems must replace the increasingly insecure system of industrialized annual monocultures (Delgado et al. 2011).

Food insecurity has been a longtime threat for much of the developing world (Sanchez et al. 1997) and many marginalized and impoverished communities in developed countries. 'Food deserts,' as some researchers call them, exist in many cities across the U.S. and disproportionately affect racial/ethnic minority neighborhoods (Walker et al. 2010). As the population rises and climate change continues to negatively impact industrial crop yields (Lobell et al. 2011), food security, access, and justice are becoming more uncertain for communities everywhere. In addition to the potential for woody crops to produce food and sequester carbon on an industrial scale, research shows they can be useful in urban forest and farm systems (Long and Nair 1999). Communities and individuals can benefit from selling fruits and nuts to farmers markets or feeding themselves directly (ibid).

In the U.S., non-renewable energy sources still dominate our supply with petroleum providing 40% of our energy, coal providing 23%, and natural gas providing 23% (Payne 2008). Transportation, which includes the 217 million cars, buses, and trucks making their way across the roads, consumes 67% of the nation's oil (Bullard 2009). The Energy Information Association estimated that in 2018 CO_2 emissions by non-renewable fuel sources reached more than 5.2 billion metric tons in the U.S. (EIA 2019). In terms of agricultural emissions, the U.S. alone emitted more than 540 million metric tons of CO_2 in 2017. Agricultural activities (not including food processing) are responsible for about 8.4% of total U.S. greenhouse gas emissions (EPA 2019) and fertilizer production is responsible for up to 1.2% of all anthropogenic GHG emissions (Woods et al. 2010). In addition to direct agricultural emissions, transportation plays a large role in food systems, and thus contributes to emissions associated with agriculture. In the U.S., food travels 1020 miles on average to get from farm to plate (Weber and Matthews 2008). As their 'non-renewable' label indicates, these energy sources are due to run out in the near future, and humankind needs to be prepared with alternatives when it does. Many ideas have been proposed to mitigate CO_2 emissions through both reducing and sequestering emissions. As plant life (especially trees) and soils are natural CO_2 sinks, it makes sense to save large forests from destruction and replant wherever we can to aid in the natural sequestration of carbon from our atmosphere. In addition to sequestration, plants may also produce materials that can be utilized as an alternative to fossil fuels, and to create a carbon recycling operation (McCarl et al. 2008).

Fortunately, researchers of environmental sustainability are investigating ways in which we can simultaneously reduce carbon emissions and feed our vulnerable and increasing populations (Horrigan et al. 2002).

1.2 Woody agriculture as a solution

The term "agroecology" encompases a range of alternative crops and forms of agriculture including perennial grasses, woody crops, silvopastures, and permaculture that have been proposed to mitigate carbon emissions and produce food, renewable fuel, and fiber. While the production methods included vary considerably, what is similar among them is the emphasis on on mimicking desirable characteristics of natural ecosystems such as higher rates of internal nutrient cycling, greater emphasis on perennial plant species, higher biodiversity, and carbon sequestration. Agroecologists seek to use these ecological principles to provide food, energy, shelter, and waste recycling (Mollison 1988). In silvopastoral systems, for example, perennial grasses sometimes combined with legumes, are planted between rows of trees. This creates livestock pastures in which animals graze between trees and are protected from sun and cold wind in extreme weather (Kallenbach et al. 2006). Instead of totally clearing forested areas for animal pastures, carbon is stored in the trees that are left and the perennial cereals that are grown for animal consumption. In contrast to short-lived annuals, non-woody perennial plants live for multiple years by regrowing from their rootstock; these deep, long-lived roots store carbon, reduce soil erosion, increase soil water infiltration, and maintain soil carbon (González-Paleo et al. 2016). Some important perennial staples include: nut & fruit trees, alfalfa, wheat, oat, barley, rye, and quinoa. Organizations like the Land Institute work towards popularizing and producing useful non-woody perennial crops by domesticating wild perennials and even perennializing annual crops (Crews et al. 2018). Woody crops provide many ecosystem services including carbon sinks, clean water, healthy soils, and biomass supplies (Zalesny et al. 2016). Temperate woody plants can store up to 1.82×10^4 kilograms of carbon per hectare per year (Rutter 1989), whereas most of the carbon fixed by annual crops is cycled back into the atmosphere as CO_2 or methane within a year (Rutter 1988).

The term "agroforestry," which is similar to agroecology but focuses specifically on the role of trees, was coined in the 1970s. Even though the term was invented recently, this type of agriculture was used as a land management practice around the world since ancient times (King 1987). In the Americas, indigenous people practiced "multi-story agriculture," where farmers would attempt to mimic complex forest ecosystems. In Africa, "shifting cultivation" was common practice, where trees and ground crops were grown together so as to benefit from the ecosystem services of the trees (FAO 2015). In combination with agroforestry, humans have cultivated woody crops like fruits and nuts for many thousands of years (Farrington and Urry 1985). Ethnographic evidence reveals that early human gardens often had a mixture of woody and herbaceous crops including fruit and nut plants. According to Zohary and Spiegal-Raoy

(1975), the earliest domestication of major fruit and nut trees occurred in protohistoric times (6000-5000 BP) in Southwest Asia. Nuts were most likely cultivated because of their carbohydrate, protein, and vitamin-rich, oily, and flavorful properties. Ancient peoples may have used nuts for multiple purposes, for example, in Southwest Asia, pistachios were probably used for incense, resin, gum, and flour (Farrington and Urry 1985). Up until the turn of the nineteenth century, Europe was covered with large, long-established swaths of fruit and nut trees, for example in Sicily, where 18,000 hectares of almond trees grow together with cereals (Smith 2010). Up until the early 1900s, Oak-Chestnut forests were a common sight in Appalachia, and the local people used chestnut trees as a main part of their economy (Youngs 2000). They provided food, building materials, fuel, and were used for bartering. For many who lived in the mountains, selling chestnuts was the only means of buying supplies like shoes, clothing, and school supplies (ibid). Nuts like chestnuts and hazelnuts are high in carbohydrates, proteins, lipids, and fibre (Xu and Hanna 2011; De la Montaña Míguelez et al. 2004); this is a main reason humans have been consuming them since ancient times (Mehlenbacher 1991). It is only recently that agroforestry has been replaced by high-yield, single varieties of annual monocrops. Currently, in the U.S., fruit and tree nuts are produced on only 2% of agriculture cropland (USDA ERS 2019). Jacques and Jacques (2012) argue that this transition occurred because of the political and economic arrangement of the Green Revolution and a post-war focus on economies of scale and export-oriented growth.

There are several reasons why the annual monocrop industry has come to dominate; I will be focusing on a small portion of the most recent history. Since 1950, the world's population has grown from 2.6 billion to over 7 billion, requiring a significant increase in food production. From 1950 to 2004 soybean production increased nine times, and meat production increased almost five times. Tasty and nutritious foods were available at very low prices, which made tree crop agriculture appear less urgent. Additionally, it is difficult to fit tree crop agriculture into an industrial agriculture model, unlike annuals. Tree crops require more time and labor for cultivar development and generally have hard shells that require cracking (USDA ERS 2018b; Molnar et al. 2013). Finally, policy makers have had a narrow vision focused on annual agriculture and do not, for example, include tree nuts in income support programs (USDA ERS 2019).

Walnuts, pecans, almonds, and hazelnuts are nut trees with the potential to grow in varying climates under varying conditions and that produce nutritional food for humans. They are very versatile and can be used on their own or to make different products; often they are used in baked goods, prepared foods, as snacks, milk, and more. Propagation and management techniques, planted acreage, as well as yield differ substantially among nut species (Table 1). Today's walnut industry is dominated by the Persian walnut (*Juglans regia*) which was brought over to the U.S. from France and Spain in the late 1800s (Molnar et al. 2013). 99% of the industry is located in California because of the detrimental effect of cold frost on walnuts. Walnut orchards were originally planted with individual seedlings, however this proved to create inconsistent yields, thus eventually the entire industry adopted grafting (Coppock 1994). Harvest is done by mechanical shaking, sweeping into a windrow, collecting, hulling, and drying (U.C. Davis FNRI a). Pecans are native to south-central North America and are differentiated by their long growing season and relatively late blooming characteristics (Molnar et al. 2013). They are commercially grown in 15 states in the Southern Midwest, South, and West in both groves and orchards. The most common methods of pecan propagation are grafting and budding; sexual propagation is used to produce seedling rootstocks for grafting cultivar clones (U.C. Davis FNRI e). Mechanical harvest, similar to that of walnuts, is utilized to harvest pecans (U.C. Davis FNRI d). Almonds were introduced to the U.S. in the 1840s from central and southwest Asia. Commercial industry is limited to California because almonds need mild, wet winters and hot, dry summers to thrive (U.C. Davis FNRI c). Almond trees are reliant on insect cross-pollination, in contrast to the other nut trees that rely on wind pollination, thus at least two types of almonds must be grown in alternating rows (ABC). These trees are also propagated by grafting onto rootstock, as this ensures uniformity, productivity, and specific harvest dates (Preece and Debuse 2014). Almonds are also harvested with a mechanical shaker and collected off of the ground for processing (U.C. Davis FNRI b). In terms of water requirements, almonds have one of the highest. In 2010, 3.8 million acre-feet of water was applied to almonds in California compared to 2.2 million acre-feet of water applied to other fruit & nut trees (Cooley 2015).

Type of Nut	**Pollination**	**Propagation Technique**	**Management Technique**	**Total Production Area (U.S.) (Acres)**	**Total Yield (U.S.) (U.S. tons)**
Walnuts	Wind	Grafting or budding	Mechanical shaking, sweeping into windrows, collecting	335,000 (USDA NASS 2017b)	690,000 (USDA NASS 2017a) [in-shell]
Pecans	Wind	Grafting or budding	Mechanical shaking, sweeping into windrows, collecting	398,900 (USDA NASS 2018a)	150,185 (USDA NASS 2018c) [in-shell]
Almonds	Insect	Grafting or budding	Mechanical shaking, sweeping into windrows, collecting	1,030,000 (USDA NASS 2017e)	1,133,000 (USDA NASS 2017c) [shelled]
Hazelnuts	Wind	Tie-off layering, grafting, softwood cuttings, microcuttings	Waiting for nut drop, sweeping into windrows, collecting	40,000 (USDA NASS 2017d)	32,000 (USDA NASS 2017f) [in-shell]

Table 1. Comparative information on different types of nuts.

Wild hazelnuts are native to the temperate Northern Hemisphere and more specifically in the U.S., the Eastern states. Commercial hazelnuts are currently cultivated in Europe, Asia, North America, South America, Africa and Australia (Sullivan et al. 2014), however most commercial production occurs in Turkey, Italy, Spain, and the U.S. in temperate areas with mild, wet winters and cool summers. Turkey produces 70-80% of the world's crop, while the U.S. produces less than 5%. The U.S. industry is predominantly located in the Willamette Valley of Oregon and grows hazel trees that are derived from wild, *Corylus avellana* plants introduced from Europe. These trees are native to both Europe and Western Asia. Recently, breeding efforts in the U.S. have increased to select for favorable traits like larger nut size (Molnar et al. 2013). Hazels grow naturally as a shrubby tree with multiple stems, however in the United States commercial hazelnuts are usually grown as a single trunk tree which requires pruning. They are typically grown with a single trunk to make it easier to use a mechanical sweeper to sweep the nuts from underneath the tree. In Oregon, hazels are not considered commercially productive until age 4; mature orchards can produce from 2.24-4.48 tonnes of dry in-shell nuts/hectare and can remain productive for up to 50 years (Olsen 2013b). Commercial hazelnut plants are not usually coppiced, though they are pruned in very particular ways to promote strategic branch growth, renewal, and high yields (OSU). In addition, they are commonly propagated using tie-off layering (like simple layering but uses the current season's shoots), grafting, softwood cuttings, and microcuttings. These are all methods that create genetically identical trees from parent trees (Olsen and Smith 2013). Harvest is done by waiting for nuts to drop and then using a mechanical sweeper to sweep nuts into one or two windrows; subsequently, the pick up operation begins. Many farmers end up performing multiple harvests due to long nut drop periods and varying weather conditions; additionally, they may utilize mowing for weed management, or agro-ecologically strategic intercrops and/or cover crops (Olsen and Peachy 2013). In the U.S. in 2017, in-shell hazelnut yields were 0.8 tons/acre (1.79 tonnes/ha) with about 40,000 acres (16,187 ha) in production (USDA NASS 2017d). Hazelnuts are sold on two different markets--the in-shell market and the kernel market. The in-shell market accounts for 5-10% of the world hazelnut crop and peaks around Thanksgiving/Christmas time. The kernel market accounts for the other 90-95% of the market--this product is usually sold to snack and candy makers, bakers, and other processors (Mehlenbacher 1991). Mehlenbacher et al. (2009) calculated kernel yields for three of Oregon's successful cultivars, 'Yamhill,' 'Lewis,' and 'Barcelona.' Yields were 14, 16, and 10 kg/tree respectively. To extract kernels from shells, machines called 'crackers' are used, which compress the nut in a gap between the spindle and anvil. This gap is adjusted for nut size, thus nuts must be sorted into size classes for cracking. As we have learned, commercial nut industries are feasible and already exist; however, they should be utilized on a larger scale given the ecological and economic benefits they provide.

Before we delve into understanding hybrid hazelnuts, it is important to understand typical growth patterns of nut plants in general. These nut plants are from different families, however their life history strategies are similar enough to be able to compare them. Pinchot et al. (2015) studied American, Chinese and backcrossed chestnuts in a commercial tree nursery in Tennessee to understand effects of planted nut weight and size and temporal dynamics on seedling growth. Similar to Clark et al. (2012), they found that larger planted chestnuts generally produced larger chestnut seedlings. Additionally, they found that chestnuts that germinated earlier had a better chance of survival than those that germinated later, potentially because of shading or space. This suggests that wider spacing in nursery beds may lead to larger chestnuts (Pinchot et al. 2015). Jacobs et al. (2009) studied chestnuts in comparison to interplanted oak and black walnut; they found chestnuts exhibited more rapid growth, and greater aboveground biomass and carbon uptake than the others. From these results they recommend that chestnuts be used for carbon sequestration. Additionally, they state that chestnut wood has relatively high value and decay resistance and thus could be made into furniture or other products. Brauer et al. (2005) analyzed nut-yield variations and the relationship between nut yield and diameter in open canopy black walnut trees in multiple locations across the Southern U.S. They found that nut yields in individual trees varied considerably over time, suggesting data need to be collected for several years to get an accurate measurement of nut yield (Brauer et al. 2005). Oregon State University (OSU) has developed an extensive breeding program in which new hazelnut cultivars are planted and tested for 7 year periods. This is still going on currently. From 1990-2000, McCluskey et al. (2001) completed three trials that compared between several hazelnut cultivars; they report that nut and kernel size fluctuates with crop load. They observed the largest variation in nut and kernel size within their highest yielding cultivars. In the 1991 trial, when comparing four cultivars, they found that two of the cultivars were 25% smaller than the other two, however they produced around the same amount of nuts. In the 1992 trial, when analyzing three of the same cultivars and one distinct, they observed the heaviest crops in 1995, 1997, and 1999; all four cultivars displayed a strong biennial bearing pattern.

It is not uncommon for nut trees to be infected by certain diseases (Thousand Cankers, Pecan Scab, Chestnut Blight, Eastern Filbert Blight, etc.); some are more threatening than others. For example, Chestnut Blight spread quickly from the northeast to southwest of the U.S. in the late 1800s, devastating much of the population (Youngs 2000). This tree's wood was frequently used to build log cabins and its nuts contributed to natural ecosystems and human economies as hog and cattle feed and as a holiday food (TACF). Chestnuts are an interesting example because they were so widespread and utilized, but were not yet grown in a large-scale industrial setting.

Eastern Filbert Blight (EFB) is a canker disease caused by the pyrenomycete *Anisogramma anomala* which is endemic to the American hazel. *A. anomala* is a nonlethal parasite that causes an insignificant canker in the American hazel, however on the European hazel, this pathogen can cause cankers that may expand up to 1 m per year. Cankers girdle branches and limbs which causes canopy dieback and death in 5-12 years if the diseased limbs are not removed (Johnson et al. 1996). In the early 1900s, people tried to establish commercial European hazelnut orchards in the Northeastern U.S. but failed because the EFB could not be controlled (ibid). Currently, EFB is firmly established in western Oregon.

It is clear that these diseases can have far reaching effects for both forest nut trees and commercially grown nut trees; this is why researchers and geneticists are breeding blight resistant and cold tolerant cultivars or hybrids (Molnar et al. 2013).

1.3 Hazelnuts, Hybrid Hazelnuts, and Neohybrid Hazelnuts

Hazels (genus: *Corylus*) are at least 40 million years old and contain 15-20 species worldwide. Humans have likely been consuming hazelnut kernels for tens of thousands, if not millions of years. Hazelnut domestication most likely occurred independently in three separate areas: the Mediterranean, Turkey, and Iran (Boccacci and Botta 2009). They are consumed for their nutritional value, as they consist of ~50-70% lipids, mostly in the form of triglycerides, 10-20% protein, and are an excellent source of Vitamin E (~400mg/100g) and Vitamin B6 (~57mg/100g) (Mehlenbacher 1991). The continued existence of this plant over millions of years speaks to its ability to survive and adapt, and its potential as a food crop in the wake of climate change. In addition to direct consumption, hazelnuts have the potential to be made into oil, milk, and flour. Hazelnut oil can serve as more than an ingredient in our meals; it has advantageous cold flow properties that make it a better option than soybean oil for biofuel (Xu et al. 2007).

Commercial hazelnut production in the U.S. has been isolated to the Pacific Northwest because the climate is more suitable for the original form of these plants (non-hybridized). According to Mehlenbacher and Olsen (1997), 99% of the U.S. hazelnut crop is grown in the Willamette Valley of Oregon. This number may be slightly lower now due to the work being done to advance genetics and breeding for hazelnuts in the Eastern U.S. (Molnar, et al. 2005). Interestingly, the global hazelnut market is currently experiencing rapid growth because demand is high and there is growing interest in alternative uses for hazelnuts, such as food products like cold-pressed oil or commodity goods like biodiesel and livestock feed (Brainard et al. 2019). Macroeconomic analysis by Brainard et al. (2019) estimates that there is a market opportunity for ~70,800 hectares of hazelnut production for the midwest at this point in time.

In the U.S., institutions like OSU, University of Minnesota, University of Wisconsin, and Rutgers University have taken special interest in hazelnuts because of their status as a high value crop that does not have many insect or disease pests (Molnar et al. 2013). Additionally, the genus has large reservoirs of genetic diversity and short generation time (4-5 years to commercial productivity) which allows for fast progress of interesting breeding experiments (Molnar et al. 2013; Mehlenbacher et al. 2009). These institutions are focused on hybridization of hazelnut plants to select for beneficial traits that makes them compatible with a midwestern climate. Additionally, Badgersett Research Corporation, which is led by researcher Philip Rutter, has been privately breeding neohybrid hazels for more than 30 years (Molnar et al. 2013).

Hybrid hazels result from humans crossing two species of hazelnuts, usually the European hazel (*Corylus avellana*) and American hazel (*Corylus americana*), and can also be called hazelberts, filhazels, and trazels depending on the particular crosses. The different species depend on where a particular hazel originated. Cultivars are not the same as hybrids, as they are just plants with particularly good traits that have been selected from the wild and domesticated. The term 'neohybrid hazel' was coined by Philip Rutter, head of Badgersett Research Farm; these hazels are the result of crosses among at least three hazel species that continue to be recrossed and reselected to eventually create new and useful hybrids for humans (Rutter et al. 2015). Regular hybrid hazels are also recrossed and reselected, however there are three species involved in the neo-hybrid crossing instead of two, thus there is exponentially more genetic variability to select from.

Figure 1. American, Beaked, and European hazel clusters.
(*https://www.arborday.org/programs/hazelnuts/consortium/types.cfm*)

Neohybrid hazels are all genetically distinct and are designed to have a wide range of desirable characteristics, like cold hardiness, blight tolerance, nut taste and shape, etc. They are the result of many crosses of American (*Corylus americana*), Beaked (*Corylus cornuta*), and European (*Corylus avellana*) hazelnut species (Fig. 1). Philip Rutter utilizes a technique called "mass selection" to work with hazelnuts' genetically complex traits and produce the best trees for nut agriculture. This method consists of thousands of seedlings (called a hybrid swarm) being grown just long enough to select for vegetative health and vigor; trees that are not selected are culled. They select for these traits because they are signs of good nut and bearing characteristics later in the life cycle of the tree. Generally, Rutter's nut trees are machine-planted at very close spacings to make it easier to compare them, as any extraordinary characteristics stand out (Rutter, 1992).

The genetic variation available in the neohybrid gene pool is substantial--according to Rutter's calculations, Badgersett's hybrid swarm is 10^{150} times more diverse than the world corn genome (Rutter et al. 2015). This diversity is significant because it allows breeders to select for useful traits, like Eastern Filbert Blight (EFB) resistance and cold hardiness into their population. An industrialized hazelnut orchard bred to have these useful traits will have a much better chance of surviving variable climatic conditions and disease than an orchard of non-hybrid hazel clones or a field of genetically indistinct corn. Cloning of bush hazels (not tree hazels) has proven to be difficult, as grafting, layering, and root-cutting techniques are too expensive, too time consuming, or just do not work well. Tissue culture cloning seems to have good potential for the cloning of hybrid hazelnut trees and is being researched for commercial feasibility. Cloning will be important in a future hybrid hazelnut industry because it will allow for uniform plants and crops which are much easier to harvest and process (Rutter and Shepard 2002). Currently, neohybrid hazels have multiple stems and are not morphologically uniform. Either nut harvesting machinery needs to be altered to be more effective in a neohybrid hazel orchard, or a cloning method needs to be commercialized to allow for industrialization. According to Rutter, blueberry-picking machinery might be a good method for harvesting hybrid hazelnuts (Rutter et al. 2015). The harvesting and cloning challenges are still being investigated by experts in the field today.

In contrast to commercial growers who use various cloning mechanisms to grow hazelnut "whips" for planting, Badgersett Research Corporation raises "tubelings" from seeds to make planting easy and successful for the buyer. These genetically distinct tubelings are grown in a greenhouse to be 6-10 inches tall and as hearty as a 1-year old naturally-grown nut plant in about 3 months (Rutter 2015a). They can be used as windbreaks, living snow fences, wildlife plantings, pick-your-own farming, or whole-field plantings. A grower can tell nuts are ripe when they start falling to the ground; they can then go through the rows of trees with a mechanical sweeper. This machine sweeps nuts into windrows which can then be picked up by mechanical harvesters which separates the nuts from leaves, twigs, and empty husks. Ultimately, the nuts are dried with the passive solar method or forced-air box dryers, and stored or processed (U.C. Davis FNRI a). For neohybrid hazelnuts specifically, Philip Rutter recommends using a "direct-from-the-bush" method of harvesting because it avoids ground contamination and requires less weed removal/ground leveling. He reasons that blueberry-picking machines made by BEI, Oxbo Korvan, and Littau are the best for the job from experience (Rutter et al. 2015). An important question to ask is whether these blueberry-picker-like machines would harvest nuts that were not yet ripe, as both neohybrid hazels and commercial hazels do not ripen all at once. A key component of woody agriculture, including hazel crops, is that a large amount of biomass in the form of roots, wood, and leaves stays where it is and continues to grow, trapping more carbon as time goes on.

The U.S. Midwest holds promise when it comes to industrial-scale hazelnut farming. Currently, 3 out of the 5 top agricultural producing states are located in the midwest (USDA ERS 2016). Hazelnuts could replace soybeans because of their oil's advantageous cold flow properties (Xu et al. 2007) while also producing large amounts of food and sequestering large amounts of carbon (Rutter 1988). A study by Demchik et al. (2011), showed that the average hybrid hazelnut kernel yield across all of their Upper Midwestern sites was 0.29 tonnes/hectare. Replacing large swaths of soy with hazels would dramatically change the midwestern landscape (ibid). In the next chapter, I will further discuss the opportunity for growing hazelnuts in the midwest in relation to fertilizer and carbon sequestration.

Chapter 2: Biological Background, Fertilization, and Soils

The biology of nut trees in general and hazelnuts in particular is important context for understanding the potential of hazelnuts for both food production and carbon sequestration. In this section, I address the questions: How dependent on fertilizer are conventional agricultural systems, agroforestry systems, and woody crop systems? How does fertilization affect carbon sequestration in hazelnuts? What role does coppicing play in commercial hazelnut agriculture versus Rutter's neohybrid hazels? How do levels of soil organic matter compare in different types of agriculture?

Hazelnuts, chestnuts, almonds, pecans, and walnuts fall under the category of deciduous trees. They are perennials, meaning they flower and reproduce for many growing seasons. Because they must survive multiple growing seasons, they generally tend to delay reproduction for the first few years and devote most of their energy to the production of structural woody biomass, including extensive root systems. Additionally, many nut plants are mast-producers, meaning they produce abundantly one year and then have moderate or low production the next year (Koenig and Knops 2005). Weather, species type, genetics, and ecosystem factors are believed to play a large part in determining a plant's mast cycling.

Hazel species are divided into three subgroups, two of which grow in a "bush-like" manner with multiple stems and one of which comprises genuine trees that grow up to 110 ft. All types of hazels form a broad, deep root system, and European hazels may live 500-1,000 years by regrowing stems from their rootstock (Rutter et al. 2015). Thus, within the bush-like varieties, most long-term carbon storage occurs in the soil and roots underneath the trees. Hazels are monoecious, which means each individual plant separately bears both male and female flowers (Fig. 2). They are anemophilous (wind-pollinated) and dichogamous, meaning the male and female flowers mature at different times, thus promoting cross-pollination (Mehlenbacher 1991). Compatibility of these trees is regulated by one gene; if pollen from a particular tree falls on flowers from that same

Figure 2. Male and female flower parts of hazelnuts trees. (https://oregonstate.edu/dept/ldplants/coav3.htm)

tree, the gene will not allow fertilization--this is called self-incompatibility (Olsen 2013a). The flowering period of female parts varies greatly from year to year as it is temperature dependent (Rutter et al. 2015; Mehlenbacher 1991). Male catkins form in late summer, overwinter, and shed pollen in early spring. Different varieties of trees may produce pollen late, middle, or early in the season. Olsen (2013a) recommends dispersing some of each variety throughout an orchard to take the best advantage of wind and make sure flowers are pollinated no matter when they develop.

During pollination, female flowers develop a bright red tuft of stigmatic styles, meaning they have several long styles with stigmatic surfaces that are receptive to pollen and an ovarian meristem at their base. Within 4-7 days of pollination the pollen tube grows to the base of the style, the tube with sperm gets blocked off, and a long resting period ensues. Pollination also stimulates the ovarian meristem to start developing into an ovary; this happens slowly over the next 4 months with rapid growth during the last 5-6 weeks. Once the ovary is a mature organ containing egg cells, the resting sperm becomes activated, secondary pollen tubes begin to grow, and fertilization occurs (Olsen 2013a). The number of stigmas and thus ovaries corresponds to the number of nuts in a cluster. Each individual hazelnut has a hard shell and a husk surrounding it; the husk serves as a defense barrier and can have a wide range of characteristics like chemical weaponry or glandular hairs (Rutter et al. 2015). The time period that nuts drop depends on husk morphology and nut maturity (Mehlenbacher 1991).

Organic carbon compounds are the vehicles that plants use to store and transfer energy (Mooney 1972). Through photosynthesis plants fix atmospheric carbon dioxide to produce simple sugars which are then converted into a variety of different plant tissues. Organic matter, or biomass, is made up of approximately 50% carbon (Brown and Lugo 1982), 47.8% in hazelnuts (measured by averaging tissue types) (Jagodzinski et al. 2012), thus by measuring biomass in the form of various living plant tissues and decomposed tissues that become incorporated into the soil, we can calculate the amount of carbon a plant has stored. Biomass, carbon storage, and food production in plants can be affected by fertilizer.

The majority of large commercial agricultural systems in the U.S. today rely on the use of fertilizers, commonly consisting of nitrogen and phosphorous. According to the USDA fertilizer use workbook, the commercial corn industry applied an average of 0.16 tonnes/ha of nitrogen and 0.07 tonnes/ha of phosphate on fields in 2016 across the U.S. (USDA ERS 2018a). The commercial soy industry applied an average of 0.02 tonnes/ha of nitrogen and 0.06 tonnes/ha of phosphate on fields in 2015 (ibid). Even agroforestry systems, in which crops are grown among trees, are unlikely to be sustainable without fertilization because large amounts of nutrients are removed in harvested products (Szott and Kass 1993). In woody crop systems, where every crop is a tree or bush, nutrients are removed in harvested products as well, however there is more organic matter in the form of leaves and branches being contributed to soils. This organic matter contribution may reduce the need for fertilizer. Still, in almonds and hazelnuts, for example, nitrogen and other fertilizer amounts are recommended based on soil sampling and leaf analysis

(U.C. Davis FNRI b; Olsen 2013c). According to Braun et al. (2011a), nitrogen requirements of hybrid hazelnuts vary significantly based on soil type and management conditions; factors such as nutrient deficiencies, moisture, weeds, ground cover, and mulch must be considered when making decisions about nitrogen application. The most efficient uptake of nitrogen in Oregon hazelnut trees occurs during active spring growth (Olsen 2013c). Recommended amounts of nitrogen fertilizer in the Upper Midwest are described in table 2. This is assuming P and K were applied before planting and that soil organic matter does not exceed 4.5%, in which case no N fertilizer is required (Braun and Jensen).

Year	**N to Apply**
	ounces per yard^3 of bush volume
1 (establishment year)	0
2	0 – 0.125
3	0 – 0.25

Table 2. Recommended-N rates for hybrid hazelnuts in the Upper Midwest for the first three years after transplanting (Braun and Jensen).

How nut trees allocate photosynthetic production among root, shoot, leaf and nut production is important for both carbon sequestration and food production. Resource allocation varies over the course of tree maturation; it can potentially be manipulated through breeding, fertilization, pruning, weeding and other management practices to maximize economic potential. Nut tree fertilization experiments provide some insight into the role of fertilizers in carbon allocation. Jones et al. (1995) found that spring fertilization did not increase black walnut nut production, however late summer fertilization significantly increased both nut production and diameter growth. They explain this result by the fact that their N and P nutrition was improved at a time when walnut nut production was drawing heavily on stored carbohydrate reserves. Application of fertilizer may allow for increased physiological vigor, stimulation in diameter, and number of flowers set. Jones and Haines (1998) found that over four years, nitrogen, phosphorus, and potassium fertilizer treatments (Granular NPK broadcast at rate of 0.18 kg/cm, equates to 50 kg of N per hectare treated) moderately increased nut production in Black Walnut trees *(Juglans nigra)*. According to the principle of resource allocation, a greater availability of resources leads to a greater reproductive effort in organisms (Gadgil and Bossert 1970). Braun et al. (2011a) conducted a study on four 3-6-year-old plantings of hybrid hazels in the Upper Midwest over the course of 3 years. They found that when trees were growing in soils with high organic matter, no response to nitrogen was observed. At the three sites with low organic matter, a growth response (increase in bush volume) was observed the second or third year after fertilization was initiated. They explain that a delayed response to fertilization is common in woody plants (Braun et al. 2011a).

There are not many studies that report on how fertilization affects carbon allocation in the aboveground tissues of nut crops, including hazelnuts. Some studies report on fertilization affecting nuts, leaves, and woody growth, but rarely in comparison to other tissue production. One study by Goodman et al. (2013) analyzed how nitrogen fertilization affects morphology and production efficiency in black walnuts. They found a significant difference in aboveground biomass partitioning between fertilized and unfertilized groups; the branch mass to stem mass ratio was greater in all fertilizer treatments compared to the unfertilized control. From this results, they inferred that high fertilization rates might shift biomass allocation away from stem wood and into branches. In addition, a hazelnut biology book by Mehlenbacher (1991) vaguely states that in the majority of species, extreme vigor in the wild is often associated with low yield. Based on this gap in knowledge, it is important to study how fertilization may affect nut production relative to corn and soy in addition to long-term carbon sequestration.

The amount of energy that is utilized to create fertilizer is important when thinking about the sustainability of a crop. If hybrid hazelnuts require fertilizer to produce viable nut crops, they should be storing or sequestering more than the amount of carbon that is emitted in the creation of this fertilizer. Fertilizer production uses large amounts of natural gas and coal and amounts to more than 50% of total energy use in commercial agriculture, including both crop and production systems (Woods et al. 2010). Nitrogen fertilizer production emits more GHGs than phosphate, potash, and lime combined; it also emits significant amounts of nitrous oxide and consumes 5% of global natural gas supplies (ibid). According to Elsayed et al. (2006), for every kilogram of ammonium nitrate produced in Europe, 2.30 kg of carbon dioxide is emitted. This estimate is likely similar for the United States. It is important to analyze how much carbon a hybrid hazelnut orchard is using through fertilizers and how much the fertilizers actually aid in production to understand if the crop would be truly sustainable.

Coppicing is an important part of hybrid hazelnut production as it stimulates more vigorous growth and can lead to higher nut production (Rutter et al. 2015). Rutter recommends coppicing on a regular basis, usually every 8-12 years (ibid). When coppicing occurs, the carbon that the hazels were storing in wood may be converted into biofuel or electricity through processes like combustion, pyrolysis, and gasification (Monarca et al. 2009). It is also possible to keep these woody materials inside the system by incorporating the organic matter, and thus carbon, back into the soil.

Since the beginning of settled agriculture in human populations, soils have been a source rather than a sink for atmospheric carbon (Lal et al. 2007). Estimated total CO_2 emissions from soils since 1850 is 78 ± 12 Gt on a global scale, compared to 270 ± 30 Gt from fossil fuel combustion (ibid). By now, most agricultural soils have lost 30-75% of their soil organic carbon (SOC) pool, meaning they are at very low carbon storage capacity (Lal et al. 2007) and have the potential, through management, to store more carbon. Soil organic carbon is the measurable carbon component of soil organic matter. An IPCC report published as early as 1996 identified sequestration of carbon in soil as an important greenhouse gas mitigation strategy (Cole et al. 1996). Global potential of SOC sequestration is estimated at 0.6-1.2 Gt of carbon per year (Lal et al. 2007).

SOC and soil organic matter (SOM) are highly important factors when it comes to the sustainability of crops. As mentioned above, a large amount of carbon is stored in wood in hazelnut trees, however this wood will be coppiced a number of times throughout a hybrid hazel's lifetime. According to Jose and Bardhan (2012), agroforestry systems could play an important role in reducing atmospheric CO_2 by sequestering carbon in belowground biomass and soil along with aboveground biomass. Through reviewing multiple papers, Chatterjee et al. (2018) identified mechanisms that include: efficient carbon and nutrient cycling within the soil-plant system, increased return of biomass carbon to the soil, and sequestration of soil carbon deep in the soil. In addition, soil formation, nutrient cycling, and primary production are all important contributors to larger ecosystem services like food, fresh water, and climate regulation (Chatterjee et al. 2018). In the United States, it is estimated that potential SOC sequestration is 0.14 to 0.42 Gt/year, with 0.06-0.17 Gt/year potentially sequestered in cropland by using carbon sequestration practices (Lal et al. 2007). Lal et al. (2007) reports that with increased SOC comes improvement in soil quality and thus a strong positive impact on agronomic productivity and food security.

In the last several decades, "no till" or reduced tillage agriculture for annual crops, in which the soil surface is not turned over annually, has been advanced as one approach to reducing carbon emissions or sequestering carbon. However, research on this reveals somewhat ambiguous results. Comparing conventional agriculture, no-till, and agroforestry systems, we can continue to understand the importance of soils in mitigating climate change. The meta-analysis by Chatterjee et al. (2018) concluded that SOC stocks were overall higher in agroforestry systems compared to mono-crop agricultural systems in similar climatic conditions. Additionally, older systems aged between 10-20 were more effective in improving SOC stock than systems of less than 10 years of age in every region. Conant et al. (2007) conducted a model simulation to demonstrate how converting from a zero tillage system to a continuous conventional tillage system affected soil carbon content. They found that SOC was reduced nearly 27% over 220 years in the conventional tillage system. Other researchers, like Powlson et al. (2010), present results from multiple studies that have analyzed tillage data and found that net accumulation of carbon in soils under reduced tillage systems is much less than previously claimed. They found that most of the SOC stored is near the surface, which brings a good deal of benefits to crop production (ibid), but if tilled only once, will largely be emitted into the atmosphere. Additionally, multiple studies have found that when utilized in moist environments, no-till can increase emissions of nitrous oxide (Powlson et al. 2010). Perennial crops have been suggested for their stable root systems that may contribute more organic carbon to soils than annual crops; combined with no-till, soil quality would likely be greatly improved by this system (ibid).

Woody agriculture is another approach that has been discussed and researched to reduce carbon emissions and sequester carbon in the soil. Woody tree crops are a valuable type of perennial, as they grow deep tree roots that can enhance SOC in deeper layers of soil (Chatterjee et al. 2018). A study by Berhongaray et al. (2017) showed that a short-rotation coppice site with poplar and willow increased the SOC pool from 109 to 139 tonnes C/hectare in four years with high accumulations found deep in the soil. In this case, the coppiced wood was removed from the system.

Leaf litter decomposition is another aspect of soils that is important to compare in perennial woody crops and annual crops. Through analyzing multiple studies, Cornelissen (1996) summarizes that decomposition rate of leaf litter from various species depends greatly on the physicochemical properties of their leaves. This means features like life-form, leaf habit, and taxonomy affect the way leaves decompose (ibid). Separate studies on decomposition of corn residue and deciduous leaves show that deciduous leaves decompose more slowly than corn residue, potentially leading to greater long term soil carbon sequestration. Bockheim et al. (1991) found that trembling aspen and northern pin oak had 50% of leaf litter remaining after 1.6 years and 2 years respectively. Corn residue, on the other hand, had only 20% of litter remaining after 164 days (Vazquez et al. 2003). From these results, we might expect leaves to stay be more stable and thus result in more carbon sequestration in deciduous systems.

Woody crops that are planted to produce food also have the capacity to sequester large amounts of carbon (Jose and Bardhan, 2012) and produce food high in nutritional value (Xu and Hanna 2010). Hazelnuts are being advanced as a potentially valuable crop for the midwest U.S. (Brainard et al. 2019; Braun et al. 2011a; Braun et al. 2011b). Despite this, we have not found many other studies that specifically analyze the carbon sequestration potential of hazelnut trees.

An experimental hazelnut orchard at Oberlin College, established in 2011, was designed to provide a long-term site for studying the capacity of hybrid hazelnuts to produce food and sequester carbon. This thesis summarizes the first eight years of findings on nuts, husks, leaves, wood, and topsoil organic matter and analyzes these variables with respect to time and fertilizer treatment. Previous studies have found that fertilizer application increases tree nut production (Jones and Haines 1998; Rutter and Shepard 2002; Schroth et al. 2015). Our goal throughout this investigation was to answer four specific questions regarding carbon allocation, carbon sequestration, fertilizer impact, and food production in neohybrid hazelnut trees. Does annual allocation of carbon to leaves, woody tissue and nuts change over time as hybrid hazels mature? How much carbon can a hybrid hazel system store, where is it stored, and how does this change over time? Does fertilization affect patterns of carbon allocation and long-term storage? Are genetically diverse trees capable of producing nut crops similar in scale to conventional commodity crops in the midwest?

Chapter 3: Methods

3.1 System Description

An experimental orchard of genetically diverse hybrid hazelnuts was initiated at Oberlin College (Oberlin, OH) in Spring of 2011, consisting of a 20 x 16-meter plot (0.032 ha) containing 130 hazelnut trees (see Appendix I for a photographic record of planting and various stages of orchard development). This system was intended to serve as a long-term experiment to study various attributes of plant growth, nut production, carbon storage in plant tissues and soil, and the response of these to maturation and fertilization. The broad goal of this experimental system is to further understanding of this crop's potential as an alternative to commercial annual mono-cropping that currently dominates in northeast Ohio and similar climatic zones.

Figure 3. Philip Rutter, founder of Badgersett Research Farm and breeder of the hybrid hazel stock used in this experiment, with the 2013 hazel team.

Figure 4. Tubelings. (http://www.badgersett.com/info)

The hybrid hazelnut stock used in the experimental planting was developed through a breeding program designed and developed by Philip A. Rutter (Fig. 3), director of Badgersett Research Corporation. Badgersett's first hazelnut trees were planted more than 25 years ago and are now 5 or 6 generations beyond the first generation (F1) species (Rutter et al. 2015). The planting stock was delivered as "tubelings" or "plugs" (Fig. 4), which were raised in a greenhouse to be 15-26 cm in height. This same hazelnut stock has been planted at sites in multiple temperate states including the basic collection in Minnesota, a planting in Illinois, and of course the Oberlin College orchard. The trees in the study are all genetically distinct and have considerable morphological and phenological variability, as explained in Chapter 2.

Management

Much of the management, data collection, and initial analysis of results of the hazelnut orchard was conducted by Oberlin College students, many of whom were students in Systems Ecology (ENVS316). This is an advanced, project-oriented ecology class in which students work in groups to propose, execute, analyze and report on research projects under the supervision of their instructor, John Petersen. The particular contributions of the members of various student research teams to data collection and analysis in the hazelnut project are summarized in table 4 and appendix IV.

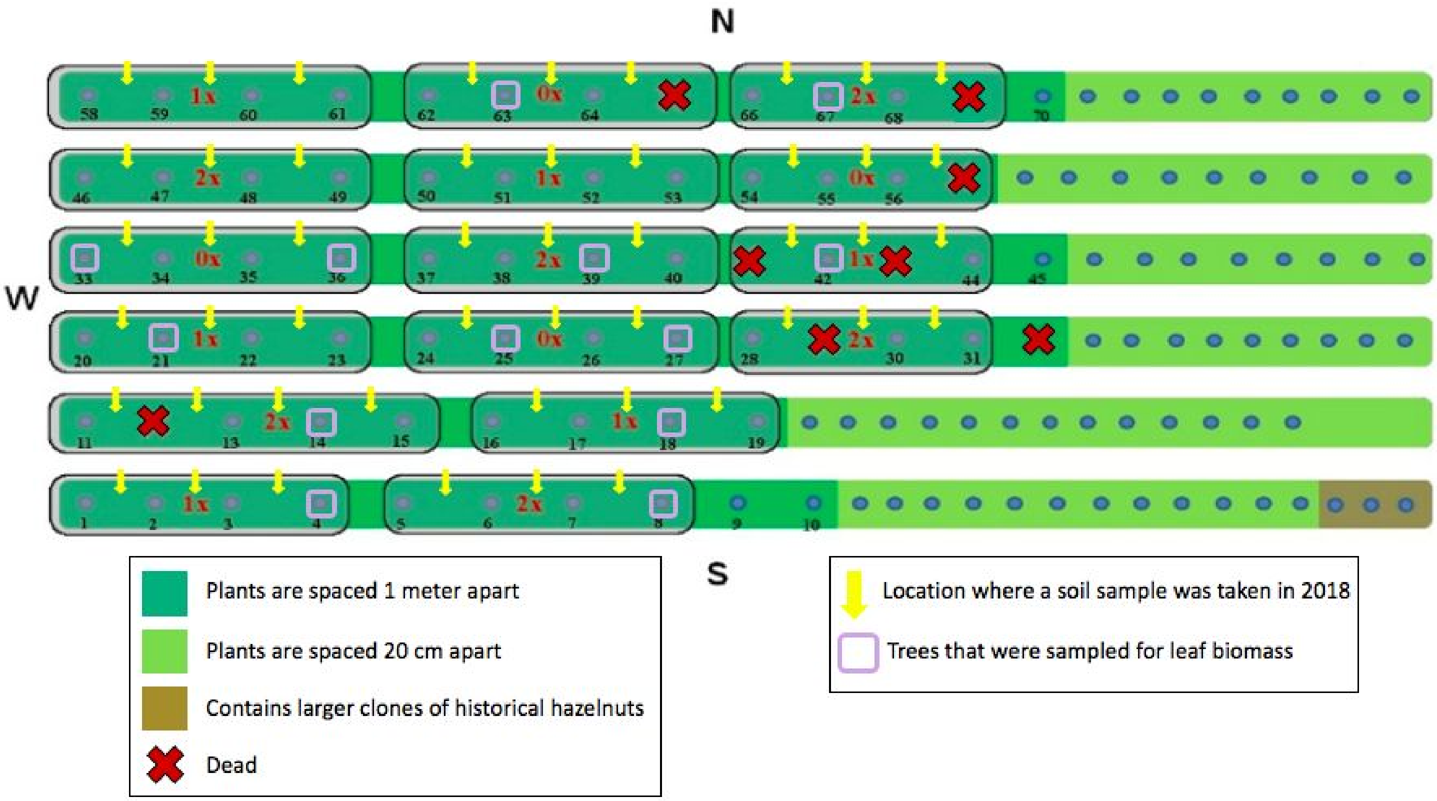


Figure 5. Map of experimental hazelnut orchard at Oberlin college. Blue dots are individual trees. Groups of trees that are part of the experiment are labeled with fertilization level and numbered. Trees that have died are marked with an X. Yellow arrows indicate locations where soil samples were taken in 2018. Trees that were sampled for leaf biomass are labeled with purple boxes.

3.2 Initial site conditions, preparation, and planting of trees

In 2008, a soil analysis was conducted of the area that was to become the hazelnut orchard to establish baseline conditions. Standard methods of texture analysis (Pansu and

Gautheyrou 2007) revealed an average of 40% clay, 27% silt, and 34% sand. Overall, with soil homogenization and fertilizer input, the Hoffman et al. (2008) research team understood the site to have favorable conditions for plant growth.

In June 2011, the research orchard was established. Prior to planting, a backhoe was used to prepare planting beds in rows. Six trenches were dug 3 meters apart and to an initial depth of 1.2 meters. These trenches were augmented with composted leaf mulch that was then mixed with the removed soil, forming slightly raised beds (referred to as "rows") for planting. Leaf mulch, which consists of organic carbon, has been found to increase edaphic properties (Athy et al. 2006), and may facilitate plant growth. The five "aisles" between each of the rows were left untouched. Within the rows, hazel seedlings were planted with three different spacings. In the westernmost dark green section, 70 hazelnuts seedlings were planted, with 9 to 13 in each bed, spaced 1 meter apart. This section was designed to serve as the site of the hazel fertilization experiment. In the easternmost light green section, 57 hazelnut seedlings were planted, with 9 to 13 in each bed, spaced 20 cm apart. The dense planting was intended to provide a nursery for replacement trees that could be used when other trees died or were removed. The small brown section in the Southeast corner is where six historic, exotic hazel clones were planted; they were quite a bit larger than the rest of the seedlings at planting (see Figure 5). Bluegrass and white clover were planted across the entire orchard for ground cover and to divert rabbits and other small animals from grazing on the hazel seedlings.

During the hazel's first three years of growth, the planted grass and clover were mowed in the aisles to within 6 inches of the plant to keep adjacent grass down to about 3 inches. Plants were watered when conditions were dry for one year after planting and not once after. After year three, maturation of the trees eliminated the need for mowing within the hazel orchard. Short grasses surrounding the trees have been allowed to grow and are mowed with the rest of the Oberlin grounds.

3.3 Current conditions

In the spring of 2019, at the time of this analysis, the trees were 8 years old. 65 of the trees planted were part of a subset of trees that were subjected to annual application of fertilizer in an experiment that was initiated one year after the initial planting (Figure 5, experimental area = 0.023 ha). 59 of these trees in the fertilizer treatment experiment remain. This is equivalent to a tree density of 2,565 trees/ha or, inversely, 3.89 m^2/tree in the system as of 2018. Three fertilizer application rates have been applied: a control group (0X) of 16 trees has received no fertilization, an intermediate group (1X) of 24 trees has received annual fertilization equivalent to application rates per unit area similar to a conventional corn field in the area, and a high dose group (2X) of 25 trees received fertilization twice that of the intermediate group.

The orchard lies in a relatively urbanized area, between a two-story house and a parking lot. There is uneven shading of the trees as a result of surrounding structures. However, trees in the fertilizer experiment were grouped into four or six replicate units spaced throughout the orchard such that that variability in shading is unlikely to have a disproportionate impact on any one treatment group.

3.4 Independent and dependent variables

As discussed, the experimental system was designed to evaluate the response of genetically diverse hybrid hazelnuts to two independent variables, time and fertilizer treatment. A regular set of measurements has been made to assess changing patterns of carbon allocation as the system develops through regular assessments of woody growth, nut & husk production, leaf production, and changes in soil organic matter.

Levels of fertilization were selected based on recommended application rates of potassium, nitrogen, and phosphorus to corn crops in this region of Northeast Ohio. Specifically, of 185 kg/ha of N, 163 kg/ha of P and 196 kg/ha of K (Lisaai, 2012). In annual crop production, fertilizer is typically spread uniformly across planted areas or within rows. Because we desired to target individual trees, we divided these areal values by number of trees so that we could determine a per tree application rate. Specifically, we calculated application as the equation: ((kg fertilizer/ha) * (total area occupied by trees in the fertilization experiment area)) / # of trees this experimental area. We selected three fertilizer treatment levels: 0X, a no fertilizer control; 1X, fertilized at the same rate recommended for a conventional corn field; 2X, fertilized at double that rate. This wide range in fertilization amounts was selected to enhance detection of a treatment effect. For trees in the 1X treatment, annual additions of each nutrient are designed to deliver 0.233 kg Phosphorus (P), 0.264 kg Nitrogen (N), and 0.280 kg Potassium (K) per tree annually. Fertilizer is purchased from a commercial agricultural supplier (Sunrise Cooperative, Norwalk OH, www.sunriseco-op.com) in the form of monoammonium phosphate (MAP), urea, and potash. Every year samples of each fertilizer are weighed and dried to determine moisture content and then additions are calculated. Phosphorus is added entirely in the form of MAP. Urea is added to make up the balance of the target nitrogen. Potash is added based on percent potassium to deliver the target elemental quantity.

Trees in the 1X and 2X treatment groups have been fertilized in early-mid summer. A 3-inch drill auger is used to dig a 7.62 cm diameter hole 46 cm from the center of each tree planting to a depth of approximately 30.5 cm. This hole is filled with the appropriate amount of fertilizer and then plugged at the top with soil so that the fertilizer is less likely to wash out of the hole in a rain event. The location of this hole is rotated by 90 degrees each year to avoid placing the fertilizer in the same location.

3.5 General tree care

Trees were watered periodically during the year they were planted. They have not been watered since then. Observation suggests that in at least one year, squirrels and birds may have significantly reduced nut harvest. Some efforts have been made to reduce squirrel consumption through the use of predator bird decoys, but these appear to have been ineffectual. We have not developed an effective approach for either excluding animals or quantifying their impact. However, in most years unconsumed nuts that were inadvertently missed during the harvest (described below) are still present below the trees. We take this as evidence that in general nut consumption is likely a small percentage of nut production.

Other than shoots that were removed for allometric calculations used to estimate biomass, described below, no pruning was done on the trees between planting and the time of this study. By the fall of 2018, the conclusion of the data reported here, the trees had reached a height of approximately three meters and high enough density that it was difficult to walk down the aisles to harvest nuts and make measurements. In January of 2019, after all data collection reported in this paper was complete, every other row of trees was coppiced, starting with the northernmost row adjacent to the parking lot. Shoots will be allowed to develop from the cut trees and we anticipate coppicing the other rows in January of 2020. This alternation should allow the orchard to maintain nut production.

Data Collection

3.6a Harvesting nut/husk clusters

Nuts are harvested manually by staff and student assistants when ripe, usually in September. The genetic variation among the planting stock results in nut ripening times varying by up to several weeks among the trees.

Nut ripeness is determined by peeling back part of the husk and pushing on a nut; if the nut comes loose in 2-3 tests of nuts from the same tree, the tree is deemed ready for harvest. Because the trees are genetically diverse, some will ripen before others; nuts from trees with fallen nut clusters are harvested first. To harvest, ripe nut clusters are twisted off at the petiole. An effort is made to avoid ripping off any parts of the stem from which clusters are growing. In our experimental protocol, great care is given to separating nuts from each tree into different paper bags labeled with the tree ID#. Bags were placed in a sunroom that was vigorously ventilated with fans to hasten drying and minimize the development of mold on husks or nuts.

Detailed harvest instructions, which describe how to recognize ripe nuts, are maintained by staff and shared with harvesters. At every harvest session at least one trained leader is present to give instructions to harvesters.

3.6b Determining nut and husk biomass

Measurements of nut and husk production began in 2014, the first year of nut production, and were repeated annually. Nuts were harvested in 2016, but no measurements were made. The total annual dry weight of nut and husk material harvested from each tree was determined as follows. First, the total air-dried weight of nuts & husks harvested from each tree was measured directly. A random subsample of 25-60 nuts was then gathered from each tree and nuts and husks were then manually separated and weighed (Fig. 6). These subsamples were then dried at 105°C (VWR model #1670 drying oven). In the first year of nut production, student researchers measured the weight of these subsamples at multiple intervals during the drying process and determined that little loss was evident after 48 hours, which has been used as a minimal drying time. A separate wet to dry weight conversion factor is calculated for both nuts and husks from each tree and these factors are applied to estimate total annual dry weight production of nuts and husks. A nut to husk ratio is also calculated from dry weight estimates.

Figure 6. Two student researchers de-husking hazelnuts for weighing and drying.

The air-dried nuts have been used for a variety of purposes including sale at local farmer's markets to explore the local market for hazelnuts and donations to a local food pantry. A consideration of the economic value of hazelnuts in local markets is beyond the scope of the analysis presented in the present study.

3.7a Estimating biomass of woody stems

The total aboveground woody biomass of each tree in the fertilizer experiment was estimated in 2011, 2013, 2014, 2015, 2017 and 2018. Allometric equations are widely used to estimate the volume and biomass of woody plants (Seidel et al. 2011). For example, in forestry, harvestable lumber from a tree of a given species is often estimated from a combination of "diameter at breast height" and tree height. Allometric equations can also be used to estimate carbon storage (Thomas and Martin 2012), including in nut trees (Prayogo et al. 2018).

As described earlier, the hazel stock used in Oberlin's experimental orchard is of shrubby or bushy form in which each plant has multiple stems extending up from the soil rather than a single dominant trunk. For this study, allometric equations were developed so that woody biomass could be estimated from the basal diameter of the multiple woody stems associated with each plant. Although we are unaware of previous studies that have used allometry to quantify the biomass of hazelnut plants, He et al. (2018) were able to quantify a strong relationship ($R^2 > 0.9$) between basal diameter and the biomass of similarly shrubby plants in a boreal fen in Canada.

From 2011 to 2015, when the plants were small (all less than 1 cm in diameter at 10 cm height) the diameter of every stem associated with each plant was measured at 10 cm above ground level. In 2017 and 2018, when stems were substantially larger, the procedure was modified; diameter was measured at 25 cm above ground level. In 2017 and 2018 stems that were smaller than 1 cm in diameter at 25 cm height were not measured. If stems split below 25 cm and were larger than 1 cm these were counted as separate stems. Given the high degree of morphological variability in branching among plants in this hazelnut orchard, it was not clear that basal diameter alone would be sufficient for developing an allometric estimate of stem biomass.

Representative stems were harvested in 2013, 2016 and 2018 to develop allometric relationships. In 2013, Xue et al. selected stems from 18 trees, six from each treatment group, for harvest. Diameter of these stems was measured at 10 cm, stems were then dried for 72 hours at 105°C and dry mass was measured. As described below, a standard allometric equation was used to quantify the relationship between diameter and biomass.

In 2016, Hobbs and Musante completed a second round of sampling. Stems were again sampled from each fertilizer treatment group. In this case, they were air-dried for six months and then weighed to assess biomass. By this time, the trees were more complex in their branch morphology and Hobbs and Musante classified the branch types into 5 groups (Fig. 7). However, no clear differences were evident in relationships between stem diameter and biomass in these different groupings.

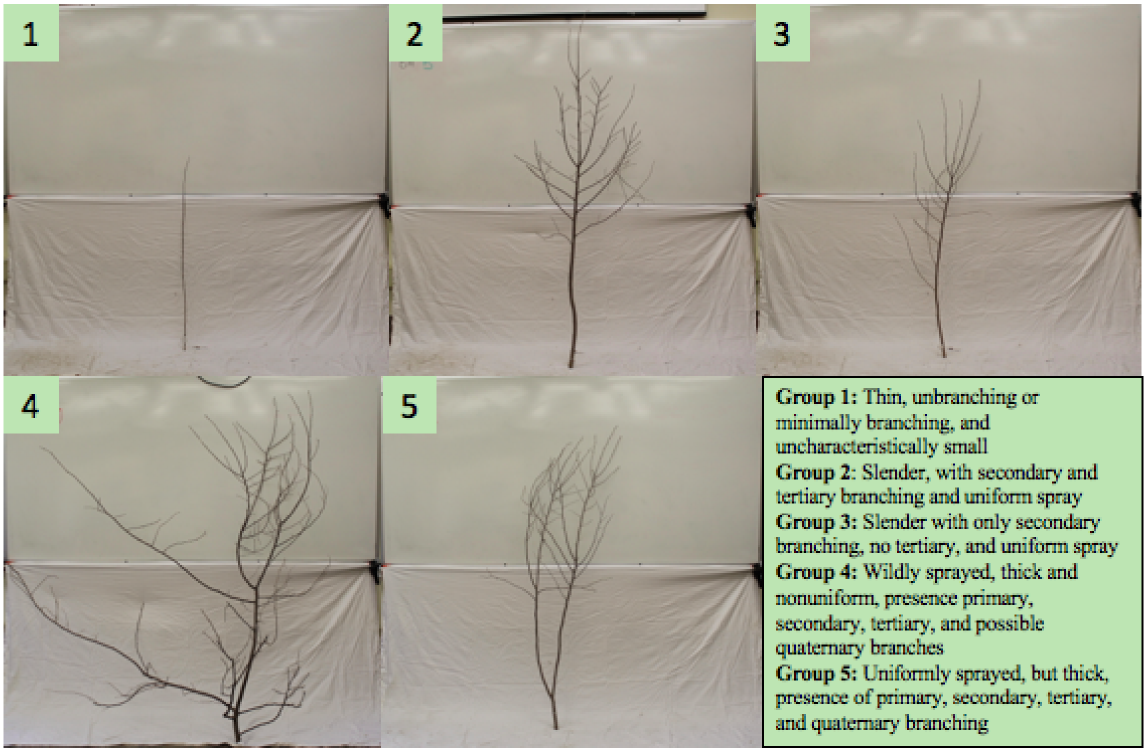


Figure 7. Branch morphology as categorized by Hobbs and Musante (2016).

In the fall of 2018, an additional set of stem samples were taken and a comprehensive allometric analysis was conducted. Stems were harvested from 16 trees; four from the 0X treatment, six from the 1X treatment, and six from the 2X treatment. In order to capture differences that might be evident in different sized stems, the second largest and second smallest stem of each tree was harvested. Additional measures of stem branching and stem length were made on the 32 harvested branches to determine if these might strengthen the allometric equation. Specifically, the number of branches coming off each main stem that were above 1 cm in diameter were counted. Stem length was measured from base to farthest branch tip. Following physical measurements, each of the 32 harvested stems was chipped in a mechanical chipper so that even the large branches could then be easily dried. The chips from each stem were kept separate from each other in labeled bags (Fig. 8). Chips were oven-dried until there was no moisture loss and weighed as in 2013.

Figure 8. Student researcher sorting chipped branches.

3.7c Developing allometric equations

Allometric equations for woody plant growth typically fit size measurements to power equations of the general form:

$B_A = \alpha D^\beta$

where B_A is biomass of an individual tree (or stem in our case), D is diameter, and α and β are coefficients that are fit through regression. Additional terms such as plant height (or stem length) and number of branches can be added as additional terms to this regression equation. For example, a multiple regression equation that considers the three measures made in the fall of 2018 is of the form:

$B_A = \alpha D^\beta + q*(\# \text{ of branches}) + h*(\text{branch length})$

where q and h are additional fitted coefficients for each stem.

Multiple different regressions were conducted to assess: the strength of the basic relationship between biomass and basal diameter; whether fitted coefficients changed over time; and whether the additional measures of number of branches and or branch length substantially improved the strength of the allometric equation. These data are summarized in table 3. Table 3 summarizes a series of regressions conducted on the biomass data collected in 2013, 2016 and 2018.

Table 3. Allometric equations including measurements of different factors and different years. (Gerrits et al. 2018).

Mass = (slope * diameter exponent) + (q * # of branches) + (h * length)					
Equation	Slope	Exponent	q	h	R2
1) 2018 (Diameter)	53.9	2.37	N/A	N/A	0.91
2) 2018 (Diameter, #Branches)	47.1	2.32	34.99	N/A	0.94
3) 2018 (Diameter, # Branches, Stem Length)	28.1	2.61	41.11	0.24	0.95
4) 2016 (Diameter)	45.9	2.28	-	-	0.84
5) 2013 (Diameter)	241.4	2.66	-	-	0.95

As indicated in Table 3, a strong allometric relationship between biomass and measured parameters was evident ($R^2 > 0.84$ in all cases). While considering number of branches coming off the main stem and length of branches did increase the strength of the relationship, the improvement was small (R^2 of 0.91 vs. 0.95) and does not appear to warrant the considerable additional effort necessary to make these measurements on each stem. Finally, the regression coefficients, particularly the slope, were substantially different in 2013 from subsequent measures. This is not surprising given that all stems were still less than 1 cm in diameter in 2013, while stems less than 1 cm in diameter were not even included in the subsequent measures.

Given this substantial difference in coefficient values, the coefficient associated with equation #5 in table 3 was used to estimate biomass from basal diameter measures made in 2011 and 2013. For consistency, equation #1 was uniformly used to estimate biomass in all subsequent years because of the high R^2 value and because the branches were only measured in 2017 and 2018. The biomass of each plant was estimated by applying the allometric equation to each stem and then adding up the biomass of all stems associated with each plant.

3.8a Estimating leaf biomass

In 2013, 18 trees were selected for leaf harvesting, six from each fertilizer treatment group (see Figure 5 for locations). In order to address variability in shading, an effort was made to maximize the space between selected trees. For consistency, leaves from these same trees were collected each year leaf data were collected. In the autumn, before leaves begin to fall, these trees are loosely but completely wrapped in nylon deer netting. In late autumn, after the leaves drop, they are manually collected in paper bags (Fig. 9). Leaves from each of these trees are oven-dried for 24 hours at 105°C and then weighed to estimate biomass.

Figure 9. Student researchers collecting leaves from hazelnut trees.

3.9 Measuring soil organic matter (SOM)

Soil organic matter (SOM) in the hazelnut orchard was measured in 2011 and not again until 2018. In 2011, SOM was measured immediately following planting: a year before the fertilization began and before any leaves from the small seedlings had fallen. Measures taken in that year represent baseline conditions that were not affected by the plants or treatment. Five sampling locations were established evenly throughout all the beds starting at the ends and one sampling location was created in each aisle along a diagonal from SW to NE. The locations were marked with flags. To average out local spatial heterogeneity, four 15-cm deep subsamples at each of these locations were taken using a 2.5-cm diameter soil corer; these samples were then homogenized. The subsamples were taken 10 cm away from each flag in each of the cardinal directions. Following sampling, all soil samples were oven-dried for 24 hours at 105 ºC, ground and incinerated for 16 hours at 400 ºC following standard loss on ignition methods for determining organic matter content (Nelson and Sommers 1996). It is assumed that weight lost to combustion represents organic matter; percent organic matter is calculated as 100%*(initial dry weight - post-combustion weight)/(initial dry weight).

Figure 10. Student researchers collecting soil samples.

In 2018 soil samples were taken again (Fig. 10). In order to assess fertilizer treatment effects, samples were taken between every two trees in each fertilization section (Fig. 5). Four subsamples were taken 10 cm in each cardinal direction and combined into one sample to average out local spatial heterogeneity. Samples were processed as in 2011.

Table 4. Dependent variable names, descriptions, all the years they were sampled, and the student groups that wrote reports and took data. Projects and student researchers are listed in Appendix IV.

		Sampling Year					
Abbreviated variable name	Variable measured	2011	2013	2014	2015	2017	2018
nut	Annual nut production			✔(Shriver and Takagi)	✔ (Wehr et al.)	✔ (Fireman and Halsten)	✔ (Tonra and Coe)
husk	Annual husk production			✔ (Shriver and Takagi)	✔ (Wehr et al.)	✔ (Fireman and Halsten)	✔ (Tonra and Coe)
repro	Annual reproductive tissue (nut+husk)			✔	✔	✔	✔
woodA	Annual wood production			✔	✔		✔
leaf	Annual leaf production		✔ (Xue et al.)	✔ (Shriver and Takagi)	✔ (Wehr et al.)		✔ (Tonra and Coe)
struct	Annual structural tissue (woodA+leaf)			✔	✔		✔
woodT	Total accumulated wood	✔ (Bolinger et al.)	✔ (Xue et al.)	✔ (Schenk and Scott)	✔ (Wehr et al.)	✔ (Fireman and Halsten)	✔ (Gerrits et al.)
soilT	Total accumulated top soil organic matter	✔ (Bolinger et al.)					✔ (Carr and Sahud)
LWARat	Ratio of leaf to woodA			✔	✔		✔

3.10 Statistical analysis

Analysis focused on the impact of both time and treatment. Time and fertilizer treatment are our independent variables while our dependent variables consist of everything that has been measured from 2011 to 2018: nut, husk, leaf, and wood biomass, % topsoil organic matter, and leaf to annual wood ratio. Except for soil organic matter, each tree was considered an experimental unit and data are compared and reported on a per tree basis (for example average kilograms leaf carbon per tree). As reported above, some measurements, such as nut production and total stem biomass, were measured for every tree in the experimental orchard. Other measures, such as leaf production, were only measured on a subset of the trees in each treatment. Thus, replication and statistical power to detect differences varies among measured attributes. Some variables were only measured in certain years based on how many student researchers were able to work on the system at that time (Table 4). The effect of time, fertilizer treatment, and the interaction between time and fertilizer treatment on the different dependent variables were analyzed for significance using analysis of covariance (ANCOVA) tests. Data were normalized through a log base transformation.

Adjusted p-values come from the post hoc test TukeyHSD (honestly significant difference) which was performed to understand specifically how fertilizer treatments differed from each other. The p-value is adjusted for multiple comparisons.

To understand if correlations between dependent variables were significant, we plotted them against each other and calculated the correlation coefficient (R). We then compared these values to a table of critical values (Table 3).

Chapter 4: Results

The purpose of this experiment was to answer four essential questions about hybrid hazelnuts as a sustainable food crop. How has the annual allocation of carbon to leaves, woody tissue and nuts changed over time as the trees have matured? How much carbon is being stored in the hazelnut system, where is it being stored and how has this changed over time? Is fertilization affecting patterns of carbon allocation and long-term storage? Are these genetically diverse trees capable of producing nut crops similar in scale to conventional commodity crops in the midwest? We predicted: 1) a general increase in the production of all tissues over time as the trees mature, 2) a shift in the percentage of carbon allocated to reproductive tissues (nuts and husk), 3) long term storage of carbon in both aboveground stem tissue and soil organic matter, and 4) a significantly higher production of all tissues within fertilized trees.

4.1 Analysis of covariance: effects of time and fertilizer treatment

4.1a Effects of time

Significant increases were evident in the annual production of several but not all plant tissues over time. For example, highly significant increases over all measured years were evident in annual leaf production ($F = 43.4, df = 1, p < 0.001$) (Fig. 11c). Annual leaf production increased from an average of 0.09 kg per tree in 2013 to an average of 0.38 kg per tree in 2015 to an average of 0.91 kg per tree (2.33 metric tonnes/ha) in 2018. Annual production of woody stem biomass was calculated by subtracting the previous year's estimate of total stem biomass from each individual year's estimate. We found that annual woody stem biomass did not differ significantly over time (*F = 0.25, df = 1, p = 0.63*). In contrast, annual nut and husk production increased over time, as the trees began producing reproductive tissue in 2014. However, annual production of nuts and husks after 2014 has been highly variable such that a clear statistical pattern of increase over time is not evident (Fig. 11a). In 2017, the year of maximum nut production, trees produced an average of 0.8 kg of in-shell nut biomass per tree (equivalent to 2.1 metric tonnes per hectare).

Significant increases over time were also evident in the accumulation of carbon in the form of woody stems (*F = 1258, df = 1, p < 0.001*) (Fig. 12a), and soil organic matter accumulation (*F = 96.9, df = 1, p < 0.001*) (Fig. 12b). The woody biomass that accumulated in these trees between 2011 and 2018 reached more than 4700 kg per tree (~12 metric tonnes per hectare). Using Jagodzinski et al. (2012)'s carbon conversion factor for hazelnut plants, we calculated that ~5.7 tonnes of carbon/hectare have been stored in wood in this system thus far (between 2011 and 2018), amounting to 0.8 tonnes C/ha/yr. Additionally, percent topsoil organic matter increased from 4.2% in 2011 to 7.7% in 2018 (*F = 96.91, df = 1, p < 0.001*) (Fig. 12b).

Additionally, we analyzed whether relationships among variables changed over time. Nut & husk production was too variable, and topsoil organic matter had too little data and could not easily be associated with particular trees to evaluate any important relationships with other variables. We were, however, able to evaluate the relationship between annual leaf production and annual wood production over time. We found that the ratio of leaves to wood increased from 2014 to 2018 (*F = 19.9, df = 1, p < 0.001*); this means that as time went on the trees in this orchard began to allocate more carbon to leaf production than to wood production.

4.1b Effects of fertilizer

Differences were evident in the annual production and accumulation of several but not all plant tissues between fertilizer treatments. For example, annual woody stem production differed significantly by fertilizer treatment (*F = 4.36, df = 2, p = 0.02*); there was a significantly higher annual production in 1X than 0X treatments (*p adj = 0.013*), and a marginally higher annual production in 2X than 0X (*p adj = 0.079*). Plants in the 1X and 2X groups produced significantly (about 44%) more woody stem tissue each year than trees in the 0X group (Fig. 11d). We did not find any significant difference in annual nut or husk production between fertilizer groups (*F = 0.18, df = 1, p = 0.67; F = 0.91, df = 1, p = 0.34*) (Fig. 11a, b). There was less than a 0.017 kg difference in nut production between the 0X and 1X, and 1X and 2X treatments, an increase of about 4%. Annual leaf tissue did not significantly differ between fertilizer treatments *(F = 1.01, df = 1, p = 0.37).*

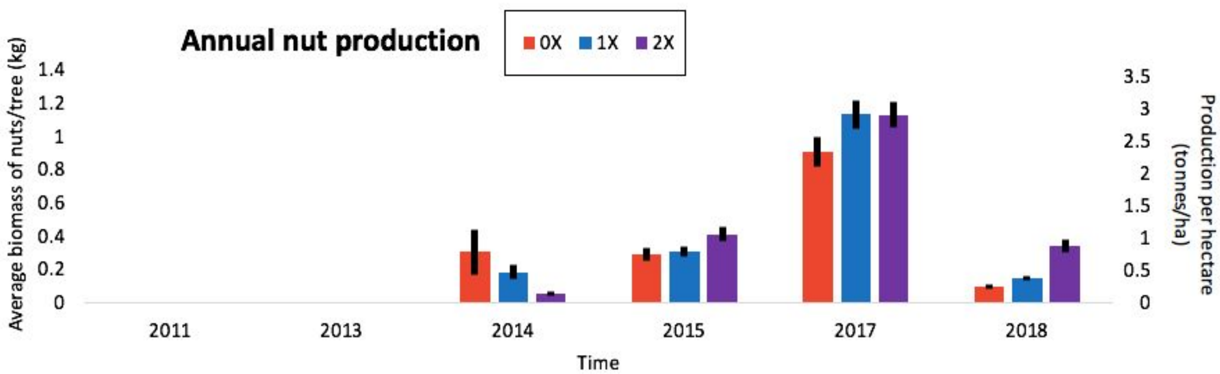
Significant differences were also evident in the total accumulation of biomass in the form of woody stems among the different fertilizer treatment groups over the 8 years of plant growth (*F = 3.86, df = 2, p = 0.02*). Trees given the 1X fertilizer treatment accumulated significantly more woody biomass than trees given the 0X treatment (*p adj = 0.018*, Fig. 11c); trees from the

1X group accumulated 59% more wood than trees from the 0X group. No statistical differences were evident between trees in the 1X and 2X groups or trees in the 0X and 2X groups *(p adj = 0.68; p adj = 0.109)*.

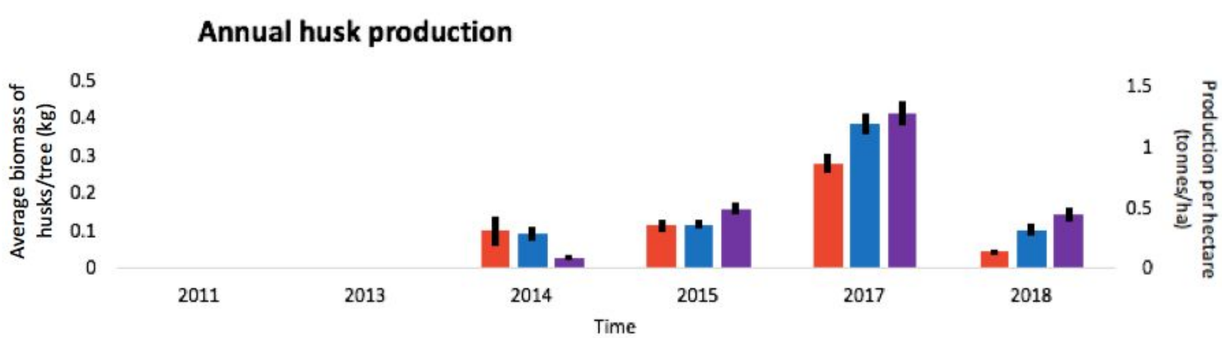
4.1c Time and fertilizer treatment interaction

We assessed whether a time by fertilizer interaction existed for nuts & husks, leaves, annual wood production, total wood accumulation, and % soil organic matter. We found no significant interactions for any of the variables examined.

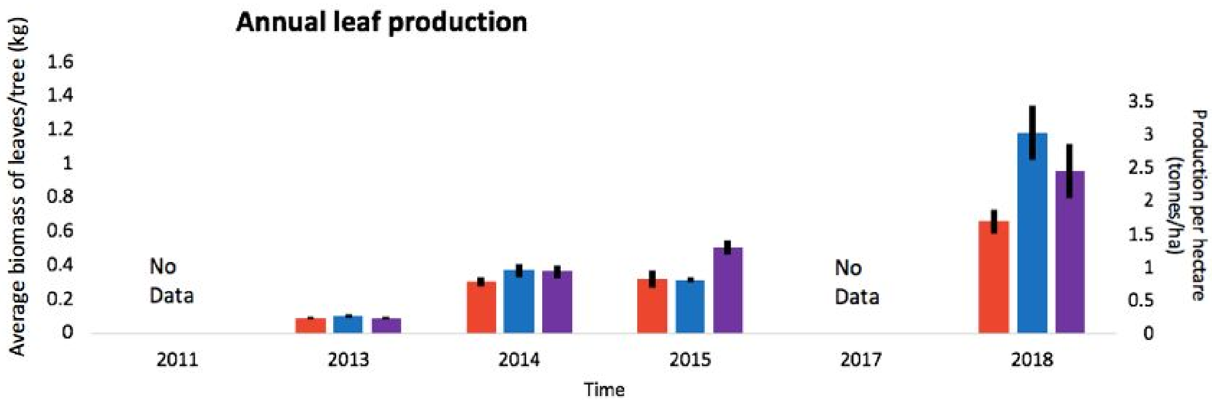
a.



b.



c.



d.

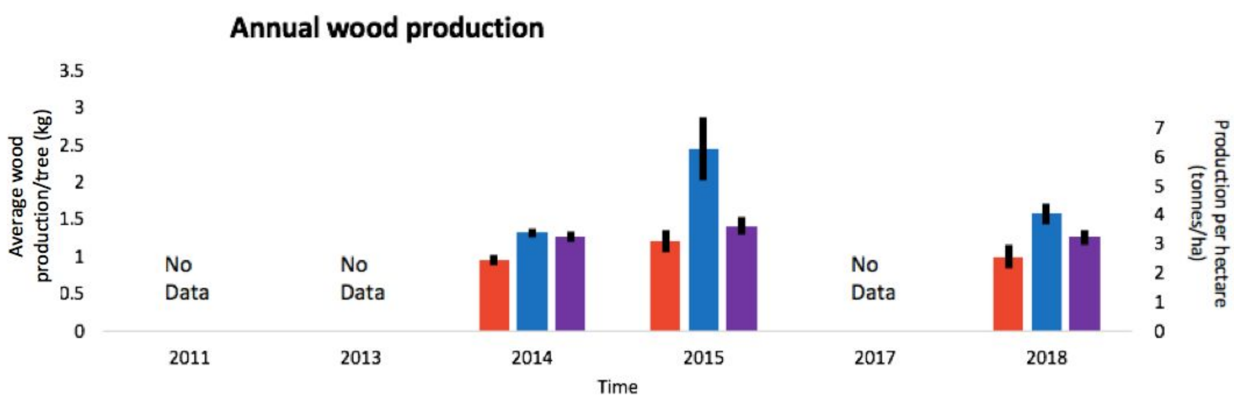
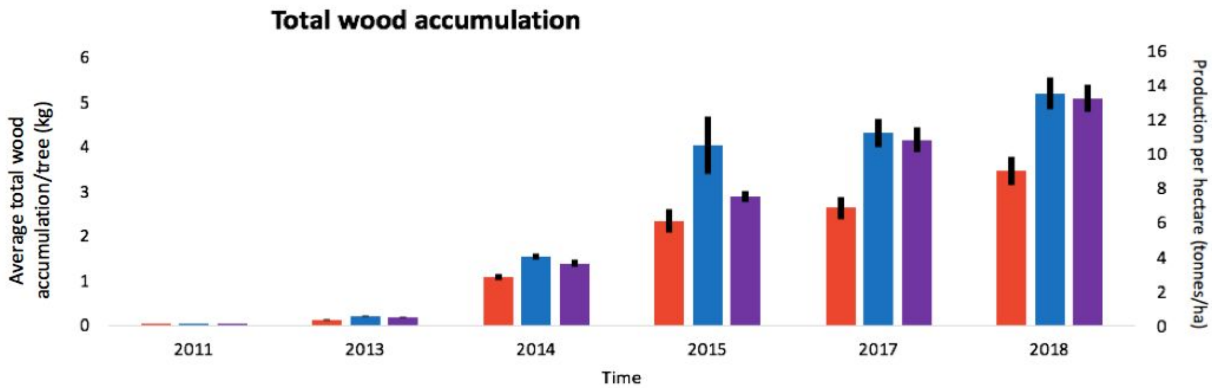


Figure 11. Mean annual production per tree and estimations on an aerial basis of nuts (a), husks (b), leaves (c), and woody stems (d) plotted against the years in which each variable was assessed. As indicated in the legend, red bars represent the average for trees in the 0X fertilization group, blue bars represent the 1X fertilization group, and purple bars represent the 2X fertilization group. Error bars are the standard error of the mean among trees in each group.

a.



b.

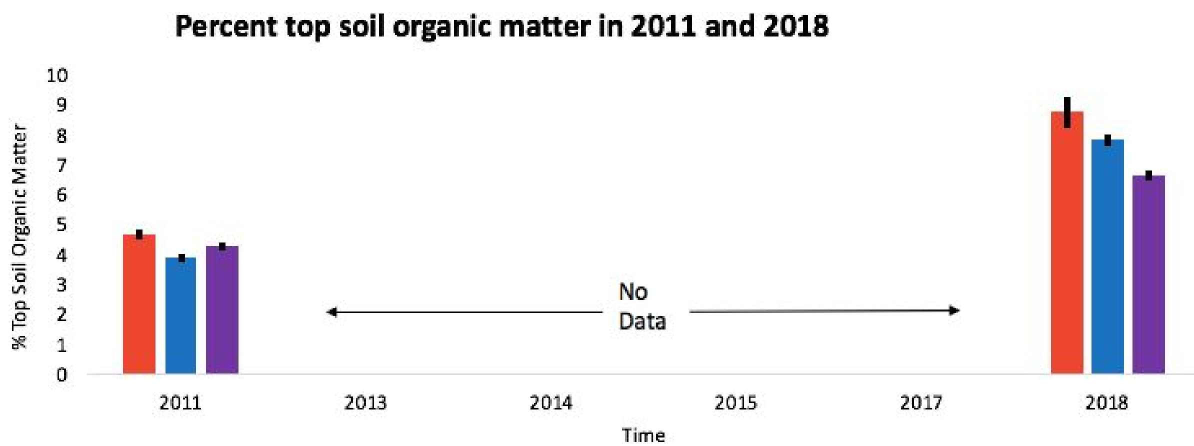


Figure 12. Accumulation of organic matter over time in different fertilizer treatment groups in woody stems (a) and in soil organic matter (b).

4.2 Correlations among variables

Using correlation coefficients and a table of critical values, we analyzed the significance of relationships between 13 dependent variables in 2018 and 2017. We only examined correlations for these two years because they were most recent and had enough data to complete the tests accurately. For 2017, year of maximum nut production, we did not find any significant correlations between nut production and total woody plant biomass ($R = 0.11$ +/- 0.349). We found only one significant correlation in 2018: total woody stem accumulation was positively correlated with annual leaf production, meaning trees that had higher woody biomass accumulation in 2018 also had more leaves ($R = 0.88$ +/- 0.532) (Fig. 13).

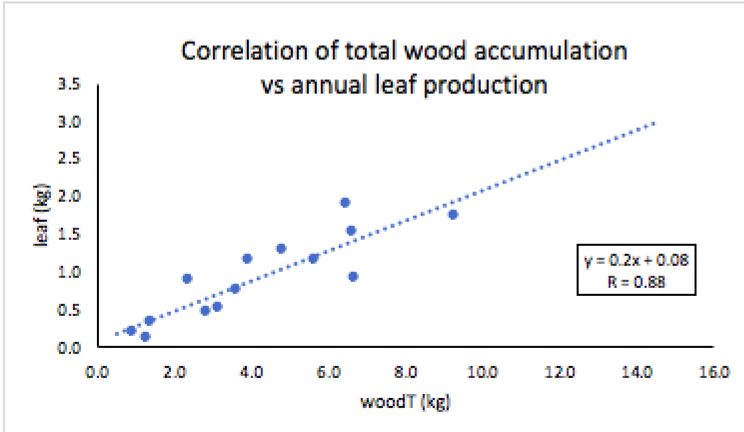


Figure 13. Relationship between annual leaf production and total accumulated wood from 2018.

Chapter 5: Analysis & Discussion

An experimental hybrid hazelnut orchard was set up at Oberlin College in a collaborative effort to study their ecological and economic potential as alternatives to conventional agriculture. This study, which reports on findings from Oberlin's experimental orchard, answers multiple questions including: How has the annual allocation of carbon to leaves, woody tissue and nuts changed over time as the trees have matured? How much carbon is being stored in the hazelnut system, where is it being stored and how has this changed over time? Is fertilization affecting patterns of carbon allocation and long-term storage? Are these genetically diverse trees capable of producing nut crops similar in scale to conventional commodity crops in the midwest?

5.1 Has the annual allocation of carbon to leaves, woody tissue, and nuts changed over time as the trees have matured?

In this study, we observed a general increase in annual leaf production, woody biomass accumulation, and soil organic matter accumulation over time (Fig. 11c, 12a, 12b). This is to be expected because as trees grow and mature, they tend to get bigger and produce more biomass each year; this is a basic part of woody plant life cycles. Since a goal was to determine if this system is sequestering carbon, the significant increase observed in soil organic matter is important. The mechanism for this seems clear, as more structural biomass is being produced then more leaf and woody tissue falls to the ground and decomposes over the years which then turns into organic matter in the soil. The hazels are growing as we expect woody plants to grow in this midwestern climate.

Annual nut production, on the other hand, turned out to be quite variable over time in this experiment (Fig. 11a). After 2014, the first year that the trees produced reproductive tissue, production increased with a peak in 2017. However, in 2018 we found production levels were almost as low as in 2014. We also found no clear relationship between tree size (total woody biomass accumulation) and nut production. Brauer et al. (2006) examined two planting sites of black walnut to understand variations in nut production over time and the relationship between trunk diameter and nut yield. They found alternate bearing patterns at both sites, with one site showing more variability than the other, however nut yields did tend to increase over the 4 and 6-year sampling times. Braun, et al. (2011a) could not make strong conclusions about nut production due to the relative immaturity of their hazelnut plants. However, they were able to conclude that larger plants produced larger nut yields, and concluded that good soil health and management practices will favor nut production. For 2017, year of maximum nut production, we did not find any significant correlations between nut production and total woody plant biomass. Nevertheless, as the trees grow further into maturity, new relationships between tissues may begin to develop.

5.2 How much carbon is being stored in the hazelnut system, where is it being stored, and how has this changed over time?

In its most productive year (2017), the experimental orchard produced an average of 0.8 kg of in-shell nut biomass per tree, which is equivalent to 2.1 metric tonnes per hectare. Rutter et al. (2015) conservatively estimated the full potential of nut production in these neohybrid hazelnut trees to be about 1.1 metric tonnes/hectare/yr. In their year of max production, our trees produced almost double that estimate. Additionally, our production amount is very close to the dry nut production range of a commercial hazelnut orchard (2.24-4.48 metric tonnes/ha/yr) (Olsen 2013b). In October 2018, the commodity price for hazelnuts was $6,960.00 per U.S. ton or about $7.67 per kilogram (USDA NASS 2018b). The orchard also produced an average of 0.43 kg of leaf biomass per tree per year (~1.1 metric tonnes per hectare per year) and accumulated about 4.75 kg of woody biomass per tree (~12 metric tonnes per hectare) over the course of its lifespan. From these results, we can speculate that Northeast Ohio is a good environment to grow these particular types of hazelnut trees. For comparison, Northeast Ohio's average corn yield was 10.8 tonnes per hectare and average soybean yield was 3.4 tonnes per hectare in 2018 (USDA NASS 2019a; USDA NASS 2019b). If consistent production could be maintained at a large scale, our results suggest that hazelnuts could produce an in-shell quantity of biomass that is near this range of soybean production while also sequestering a significant amount of carbon in woody biomass.

From 2011 to 2018, our orchard increased in soil organic matter content from an average of 4.2% to 7.7%. Using the estimated SOM to SOC conversion factor of ~0.53 from Pribyl (2010), this equates to 2.2% to 4.1% soil organic carbon. The starting percentage of 2.2 is already large compared to commercial agricultural systems, and 4.1% SOC is even larger. Gupta et al. (2009) compared sole-crop and agroforestry systems in Punjab, India and found that in the

0-15 cm soil layer the mean % SOC was 0.41% in the sole-crop system and 0.66% in the agroforestry system. Our hazelnut orchard is sequestering a much higher percentage of carbon than both the sole-crop system and agroforestry system combined. It is important to note that our study did not consider roots as an important tissue that receives and stores carbon directly and also contributes to soil organic matter. We measured soil organic matter in the surface of the soil which includes additions from leaf and twig decomposition as well as fine surface roots. Roots are likely contributing considerable amounts of carbon much deeper in the soil and so our measures of % SOM are likely significant underestimates of the sequestration that has occurred.

We calculated correlations between all dependent variables in 2018 and 2017 and found only one significant relationship. A positive correlation exists between total woody biomass accumulation and annual leaf production in 2018 (Fig. 13), meaning trees with more accumulated woody biomass had more leaves. Usually, when trees grow structurally, they will produce more leaves to sustain their energetic needs. Enquist (2002) presents a universal model of vascular plant allometry which states that the total number of leaves in a woody plant should scale with total number of branches and branch radius. Interestingly, we also found that annual leaf production increased relative to annual wood production from 2014 to 2018. From this finding, we can infer that the trees are investing more carbon in leaves rather than wood over time. The reason that they do this may be to increase photosynthesis/energy production to eventually produce more nuts in the upcoming reproductive seasons. We have not yet seen this pattern occurring within our trees, however we may see it in the future. According to Enquist (2002), growth must slow when reproduction begins, as some fraction of resources are then devoted to reproduction and not structural growth. These trees are not yet fully mature, thus they may be slowly decreasing their woody growth rate while they increase allocation of carbon to reproduction. Observing how low nut yield was in 2018, however, reminds us that reproduction is variable at this time and thus documentation and analysis of the growth of these trees into the future is imperative to understand these relationships.

We did not find correlations or relationships over time between nut production and wood or leaf production. We hypothesized that the hazelnut trees in this experimental system would begin to allocate more carbon to nut production than woody tissue growth because at 7 years old the trees are approaching maturity and because of the principle of allocation. According to this principle, greater availability of resources leads to a greater reproductive effort in organisms (Gadgil and Bossert 1970). It has been observed that the expected harvest of hazelnut trees is only 25% in year 4 and 40% in year 5 (Rutter et al., 2015). Around year 6 they begin to yield a more substantial crop, then reach full potential in year 10 (ibid). It is possible that we are not seeing this phenomenon yet because the trees are young and nut production is still highly variable over time.

5.3 Is fertilization affecting patterns of carbon allocation and long-term storage?

We found that fertilizer treatment did not impact any of the dependent variables measured except for woody biomass. Thus far we have found that trees treated with some amount of fertilizer (1X or 2X) stored more wood annually than trees that were not treated with any fertilizer (0X) (Fig. 11c). From 2017 to 2018, trees in the 0X treatment group produced about 1.0 kg of woody biomass per tree per year while the average of trees in the 1X and 2X groups was 1.5 kg/tree/yr. This is a 50% increase in woody biomass between using no fertilizer and using some amount of fertilizer. In addition, the trees treated with 1X fertilizer accumulated more woody biomass from 2011 to 2018 than trees treated with 0X (Fig. 12a). In 2018, trees in the 0X group had accumulated 3.6 kg of wood per tree and trees in the 1X group had accumulated 5.3 kg of wood/tree, a 47% difference in biomass and carbon accumulation. Based on these findings, treating hazels with the amount of fertilizer typical to commercial corn fields may generate structurally larger trees. However, as stated above, we did not find any significant relationship between fertilizer and nut production or between nut production and wood accumulation, thus at least at this stage of development, the trees would likely be just as productive and profitable without the addition of fertilizer. It is important to note that these shrubby hazels need to be coppiced periodically. Coppicing potentially takes large amounts of wood out of the system that can be used in a variety of sustainable ways. For example, wood may be converted into biofuel or electricity through processes like combustion, pyrolysis, and gasification (Monarca et al. 2009) to be used instead of fossil fuels. Wood could also be incorporated back into the hazelnut system as organic matter to enrich the soil for further hazel growth and long-term carbon sequestration. Here at Oberlin, we have initiated an experiment to assess two alternative approaches to promoting long-term storage of carbon in SOM. In January of 2019, trees in alternating rows (half of the trees) were chipped and these chips were spread in 0.5 m wide strips in three of the six aisles between the rows of trees. In January of 2020, we intend to coppice the trees that were not coppiced in 2019, subject these to pyrolysis to produce biochar, and then spread this in the three rows that did not receive the chips. Decomposition and long-term incorporation of this organic matter into the soil will be assessed over time to further explore options for combining carbon sequestration with nut production.

It is especially important to note that annual nut & husk production in the hazelnut trees did not significantly differ based on time, fertilizer treatment, or the interaction between the two (Fig. 11a). We found that trees treated with 2X fertilizer produced marginally more nut & husks than trees treated with 0X, however the p-value was greater than 0.05, so we must take this result with a grain of salt. Weak statistical differences are matched by a small effect size; for example, in 2018, the trees in the 2X fertilizer group produced an average yield of 0.45 kg of nuts per tree while trees in the 0X group produced 0.41 kg nuts/tree, this is a small 9% difference. According to these results, this type of neohybrid hazel will likely produce the same amount of food regardless of whether it is treated with fertilizer or not. This is a very important finding because of both the cost of fertilizer and the greenhouse gas emissions associated with fertilizer production.

In addition to looking at the impacts of time and fertilizer treatment separately, we analyzed how the interaction between them may have affected our dependent variables. We did not find any significant results, which means fertilizer treatment and time are not yet interacting in this system. It is possible that as time goes on, these independent variables will have a stronger effect on the trees together than separately.

Prior to planting, the soil in which all hazelnuts were planted was supplemented with composted leaf mulch. This may have mediated the effects of both the fertilizer treatment and soil organic matter accumulation. It is certainly possible, for example, that this leaf mulch contributed nutrients to all of the trees such that the addition of fertilizer was not as important as it otherwise might have been. However, the fact that annual wood production was significantly enhanced by fertilizer treatment indicates at least some aspects of growth were affected by the treatment. It is also quite likely that this leaf mulch has been decomposing over the last eight years. Our baseline measure of 4.2% SOM included leaf mulch that had been incorporated into the soil. The fact that we were able to quantify an increase in soil organic matter suggests that the input of new organic matter from leaves, twigs and roots is in excess of leaf mulch decomposition.

5.4 Are these genetically diverse trees capable of producing nut crops similar in scale to conventional commodity crops in the midwest?

This study is the culmination of six years of data collection on an eight-year-old experimental hazelnut orchard. We present some important contributions to the small body of literature focused on hazelnuts as a sustainable food crop in the Midwest. In summary, the neohybrid hazelnut stock can grow successfully in the Northeastern Ohio region without much fertilizer treatment. Regular doses of fertilizer may be used to contribute to structural growth which could potentially increase nut yield. Others have observed that smaller trees sometimes produce large nut crops (Rutter 1992). Additional time will be necessary to assess the long-term impact of fertilizer on this system. The trees can sequester large amounts of carbon in woody tissue over time and, at least in a good year, can produce almost as much dry nut material as commercial orchards. It will be very important to continue collecting data on this hazelnut orchard and documenting relationships between tissues to further understand the life histories of these crops. After all, the hazelnut trees will not be fully mature until after they reach 10 years old (Snare 2008) or even later (Rutter et al. 2015); with time they will likely stabilize nut production and begin to allocate carbon in different ways. An important challenge to consider is how the genetic diversity of these trees creates high levels of variability in ripening and nut size.

These factors will likely pose problems for commercial harvesting of neohybrid hazelnuts and thus must be researched further.

We hope that farmers will use this research to consider the viability of investing in hazelnut crops in the Midwest or similar climatic regions. Additionally, we hope farmers will be able to better understand the payoff of fertilizer on hazelnut farming and make more informed decisions on whether to invest in fertilizers for their orchards. These hazelnut trees have sequestered roughly 300 kg of carbon in aboveground woody biomass and 4.5% SOC thus far, and in 2017 alone produced 61 kg of nuts, proving them to be efficient at producing food and sequestering carbon. It is our hope that these findings will contribute to the growing body of sustainable farming knowledge surrounding the benefits and challenges of woody agriculture and the possibility of hazelnuts becoming a substitute for traditional commodity agriculture such as corn and soy crops.

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Literature Cited

ABC. California Almonds. Almond Board of California (ABC).

Athy, E. R., C. H. Keiffer, and M. H. Stevens. 2006. Effects of Mulch on Seedlings and Soil on a Closed Landfill. Restoration Ecology 14:233-241.

Baah-Acheamfour, M., S. X. Chang, E. W. Bork, and C. N. Carlyle. 2017. The potential of agroforestry to reduce atmospheric greenhouse gases in Canada: Insight from pairwise comparisons with traditional agriculture, data gaps and future research. The Forestry Chronicle 93:180-189.

Berhongaray, G., M. S. Verlinden, L. S. Broeckx, I. A. Janssens, and R. Ceulemans. 2017. Soil carbon and belowground carbon balance of a short-rotation coppice: assessments from three different approaches. GCB Bioenergy 9:299-313.

Boccacci, P., and R. Botta. 2009. Investigating the origin of hazelnut (Corylus avellana L.) cultivars using chloroplast microsatellites. Genetic Resources and Crop Evolution 56:851-859.

Bockheim, J. G., E. A. Jepsen, and D. M. Heisey. 1991. Nutrient dynamics in decomposing leaf litter of four tree species on a sandy soil in northwestern Wisconsin. Canadian Journal for Research 21:803-812.

Bohle, H. G., T. E. Downing, and M. J. Watts. 1994. Climate change and social vulnerability: Toward a sociology and geography of food insecurity. Global Environmental Change 4:37-48.

Brainard, S., K. J. Wolz, K. Keeley, A. Rodrigues, and F. J. Selosse. Overcoming Bottlenecks in the Midwest Hazelnut Industry: An Impact Investment Plan. The Savanna Institute & Hyphae Partners; 2019 March. 1 p.

Brauer, D., A. Ares, W. Reid, A. Thomas, and J. Slusher. 2006. Nut-yield Variations and Yield–diameter Relationships in Open-canopy Black Walnut Trees in Southern USA. Agroforestry Systems 67:63-72.

Braun, L., J. Gillman, E. Hoover, and M. Russelle. 2011a. Nitrogen fertilization for new plantings of hybrid hazelnuts in the Upper Midwest of the United States of America. Canadian Journal of Plant Science 91:773-782.

Braun, L., J. Gillman, E. Hoover, and M. Russelle. 2011b. Nitrogen fertilization for young established hybrid hazelnuts in the Upper Midwest of the United States of America. Canadian Journal of Plant Science 91:907-918.

Braun, L., and J. Jensen. Hybrid Hazelnuts. Rural Advantage. 1 p.

Brown, S., and A. E. Lugo. 1982. The Storage and Production of Organic Matter in Tropical Forests and Their Role in the Global Carbon Cycle. Biotropica 14:161-187.

Bullard, R. D. 2009. Addressing Urban Transportation Equity in the United States. Pages 49-58 *In* Pavel, P., editor. Breakthrough Communities: Sustainability and Justice in the Next American Metropolis, MIT Press, .

Chatterjee, N., P. K. Ramachandran. Nair, S. Chakraborty, and V. D. Nair. 2018. Changes in soil carbon stocks across the Forest-Agroforest-Agriculture/Pasture continuum in various agroecological regions: A meta-analysis. Agriculture, Ecosystems and Environment 266:55-67.

Clark, S. L., S. E. Schlarbaum, A. M. Saxton, and F. V. Hebard. 2012. Nursery performance of American and Chinese chestnuts and backcross generations in commercial tree nurseries. Forestry 85:589-600.

Cole, V., C. Cerri, K. Minami, A. Mosier, N. Rosenberg, D. Sauerbeck, and I. I. Working group. IMPACTS, ADAPTATIONS AND MITIGATION OF CLIMATE CHANGE: SCIENTIFIC-TECHNICAL ANALYSES Cambridge University Press; 1996. 75 p.

Conant, R. T., M. Easter, K. Paustian, A. Swan, and S. Williams. 2007. Impacts of periodic tillage on soil C stocks: A synthesis. Soil & Tillage Research 95:1-10.

Cooley, H. 2015. CALIFORNIA AGRICULTURAL WATER USE: KEY BACKGROUND INFORMATION. Pacific Institute :1-9.

Coppock, R. The Walnut Industry in California: Trends, Issues, and Challenges. Agricultural Issues Center; 1994. 1 p.

Cornelissen, J. H. C. 1996. An Experimental Comparison of Leaf Decomposition Rates in a Wide Range of Temperate Plant Species and Types. Journal of Ecology 84:573-582.

Crews, T. E., W. Carton, and L. Olsson. 2018. Is the future of agriculture perennial? Imperatives and opportunities to reinvent agriculture by shifting from annual monocultures to perennial polycultures. Global Sustainability 1:1-18.

Crosson, P., and J. R. Anderson. 1994. Demand and supply: trends in global agriculture. Food Policy 19:105-119.

De La Montaña Míguelez, J, M. Míguez Bernárdez, and J. M. García Queijeiro. 2004. Composition of varieties of chestnuts from Galicia (Spain). Food Chemistry 84:401-404.

Delgado, J. A., P. M. Groffman, M. A. Nearing, T. Goddard, and D. Reicosky. 2011. Conservation practices to mitigate and adapt to climate change. Journal of Soil and Water Conservation 66:129A.

Demchik, M., A. Kern, L. Braun, J. Fischbach, and K. Turnquist. 2018. Genetic diversity of American hazelnut in the Upper Midwest, USA. Agroforestry Systems 92:1507-1516.

DPIRD. 2018. What is soil organic carbon? Government of Western Australia, Department of Primary Industries and Regional Development (DPIRD), Agriculture and Food.

EIA. 2019. U.S. Economic Assumptions and Energy-Related Carbon Dioxide Emissions. U.S. Energy Information Association (Independent Statistics & Analysis).

Elsayed, M. A., A. Evans, and N. D. Mortimer. 2006. Selective life cycle assessment for ammonium nitrate fertiliser production using natural gas as a feedstock. Project NF0614 for an Environment Assessment Tool for Biomaterial.

Enquist, B. J. 2002. Universal scaling in tree and vascular plant allometry: toward a general quantitative theory linking plant form and function from cells to ecosystems. Tree physiology 22:1045-1064.

EPA. 2019. Inventory of U.S. Greenhouse Gas Emissions and Sinks 1990-2017 (Draft). U.S. Environmental Protection Agency.

FAO. 2015. Traditional Agroforestry: History. Food and Agriculture Organization of the United Nations (FAO). Last Updated: October 2015.

Farrington, I. S., and J. Urry. 1985. FOOD AND THE EARLY HISTORY OF CULTIVATION. Journal of Ethnobiology 5:143.

Gadgil, M., and W. H. Bossert. 1970. Life Historical Consequences of Natural Selection. The American Naturalist 104:1-24.

González-Paleo, L., A. E. Vilela, and D. A. Ravetta. 2016. Back to perennials: Does selection enhance tradeoffs between yield and longevity? Industrial Crops & Products 91:272-278.

Goodman, R. C., J. A. Oliet, G. Pardillo, and D. F. Jacobs. 2013. Nitrogen Fertilization of Black Walnut (Juglans nigra L.) During Plantation Establishment. Morphology and Production Efficiency. Forest Science 59:453-463.

Gupta, N., S. Kukal, S. Bawa, and G. Dhaliwal. 2009. Soil organic carbon and aggregation under poplar based agroforestry system in relation to tree age and soil type. Agroforestry Systems 76:27-35.

He, A., G. McDermid, M. Rahman, M. Strack, S. Saraswati, and B. Xu. 2018. Developing Allometric Equations for Estimating Shrub Biomass in a Boreal Fen. Forests 9:569.

Horrigan, L., R. S. Lawrence, and P. Walker. 2002. How Sustainable Agriculture Can Address the Environmental and Human Health Harms of Industrial Agriculture. Environmental Health Perspectives 110:445-456.

IPCC. 2018. Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Intergovernmental Panel on Climate Change (IPCC); 1 p.

Jacobs, D. F., M. F. Selig, and L. R. Severeid. 2009. Aboveground carbon biomass of plantation-grown American chestnut (Castanea dentata) in absence of blight. Forest Ecology and Management 258:288-294.

Jacques, P. J., and J. R. Jacques. 2012. Monocropping Cultures into Ruin: The Loss of Food Varieties and Cultural Diversity; Sustainability 4:2970-2997.

Jagodzinski, A. M., G. Jarosiewicz, P. Karolewski, and J. Oleksyn. 2012. Carbon concentration in the biomass of common species of understory shrubs. Sylwan 156:650-662.

Johnson, K. B., S. A. Mehlenbacher, J. K. Stone, J. W. Pscheidt, and J. N. Pinkerton. 1996. Eastern Filbert Blight of European Hazelnut: It's Becoming a Manageable Disease. Plant Disease 80:1308-1316.

Jones, J. E., H. E. Garrett, J. Haines, and E. F. Loewenstein. 1995. Genetic selection and fertilization provide increased nut production under walnut-agroforestry management. Agroforestry Systems 29:265-273.

Jones, J. E., J. Haines, and F. Ponder. 1998. Annual applications of N, P, and K for four years moderately increase nut production in black walnut. 33:1011-1013.

Jose, S., and S. Bardhan. 2012. Agroforestry for biomass production and carbon sequestration: an overview. Agroforestry Systems 86:105-111.

Kallenbach, R. L., M. S. Kerley, and G. J. Bishop-Hurley. 2006. Cumulative Forage Production, Forage Quality and Livestock Performance from an Annual Ryegrass and Cereal Rye Mixture in a Pine Walnut Silvopasture. Agroforestry Systems (in cooperation with ICRAF) 66:43-53.

King, K. F. S. 1987. The history of agroforestry. Pages 3-11 *In* Steppler, H. A., and P. K. R. Nair, editors. Agroforestry: A Decade of Development, International Council for Research in Agroforestry.

Koenig, W. D., and J. M. H. Knops. 2005. The Mystery of Masting in Trees: Some trees reproduce synchronously over large areas, with widespread ecological effects, but how and why? American Scientist 93:340-347.

Lal, R., R. F. Follett, B. A. Stewart, and J. M. Kimble. 2007. SOIL CARBON SEQUESTRATION TO MITIGATE CLIMATE CHANGE AND ADVANCE FOOD SECURITY. Soil Science 172:943-956.

Lobell, D. B., W. Schlenker, and J. Costa-Roberts. 2011. Climate Trends and Global Crop Production Since 1980. Science 333:616-620.

Long, A., and P. K. Nair. 1999. Trees outside forests: agro-, community, and urban forestry. New Forests 17:145-174.

McCarl, B. A., D. Gillig, H. Lee, M. El-Halwagi, X. Qin, and G. Cornforth. 2008. Potential for Biofuel-based Greenhouse Gas Emission Mitigation: Rationale and Potential Philosophical Transactions of the Royal Society B: Biological Sciences 363:789-813.

McCluskey, R. L., A. N. Azarenko, S. A. Mehlenbacher, and D. C. Smith. 2001. Commercial Hazelnut Cultivar and Advanced Selection Evaluations at Oregon State University. Acta Hort 556:89-95.

Mehlenbacher, S. A., and J. Olsen. 1997. The Hazelnut Industry in Oregon. Acta Horticulturae :337-345.

Mehlenbacher, S. A. 1991. Hazelnuts (Corylus). Pages 791-828 *In* Moore, J. N., and J. R. J. Ballington, editors. Genetic Resources of Temperate Fruit and Nut Crops II, International Society for Horticultural Science, .

Mehlenbacher, S. A., D. C. Smith, and R. L. McCluskey. 2009. 'Yamhill' Hazelnut. HortScience 44:845-847.

Mollison, B. 1988. Permaculture: a designer's manual. Tagari Publications, Tyalgum, New South Wales.

Molnar, T. J., J. C. Goffreda, and C. R. Funk. 2005. Developing Hazelnuts for the Eastern United States. Acta Hort :609-618.

Molnar, T., P. Kahn, T. Ford, C. Funk, and C. Funk. 2013. Tree Crops, a Permanent Agriculture: Concepts from the Past for a Sustainable Future. Resources 2:457-488.

Monarca, D., M. Cecchini., M. Guerrieri, and A. Colantoni. 2009. Conventional and alternative use of biomasses derived by hazelnut cultivation and processing. Acta Horticulturae 845:627-633.

Mooney, H. A. 1972. The Carbon Balance of Plants. Annual Review of Ecology and Systematics 3:315-346.

Nelson, D. W., and L. E. Sommers. 1996. Total carbon, organic carbon, and organic matter. SSSA, .

Olsen, J. a) Growing hazelnuts in the Pacific Northwest: Pollination and Nut Development. Oregon State University; 2013 Nov.

Olsen, J. b) Growing Hazelnuts in the Pacific Northwest: Introduction. Oregon State University; 2013 November. 1 p.

Olsen, J. c) Growing Hazelnuts in the Pacific Northwest: Orchard Nutrition. Oregon State University; 2013 November. 1 p.

Olsen, J. 2011. Improvements in Hazelnuts in the United States. HortScience 46:343-344.

Olsen, J., and E. Peachy. Growing Hazelnuts in the Pacific Northwest: Orchard Floor Management. Oregon State University; 2013 November. 1 p.

Olsen, J., and D. Smith. Growing Hazelnuts in the Pacific Northwest: Plant Propagation. Oregon State University; 2013 November. 1 p.

OSU. A Basic Guide to Pruning Hazelnut Trees. Oregon State University Extension Service.

Pansu, M., and J. Gautheyrou. 2006. Handbook of Soil Analysis: Mineralogical, Organic, and Inorganic Methods. Springer-Verlag Berlin Heidelberg.

Payne, J. E. 2008. On the dynamics of energy consumption and output in the US. Applied energy 86:575-577.

Pinchot, C. C., S. L. Clark, S. E. Schlarbaum, A. M. Saxton, S. S. Sung, and F. V. Hebard. 2015. Effects of Temporal Dynamics, Nut Weight and Nut Size on Growth of American Chestnut, Chinese Chestnut and Backcross Generations in a Commercial Nursery. Forests 6:1537-1556.

Powlson, D. S., P. J. Gregory, W. R. Whalley, J. N. Quinton, D. W. Hopkins, A. P. Whitmore, P. R. Hirsch, and K. W. T. Goulding. 2011. Soil management in relation to sustainable agriculture and ecosystem services. Food Policy 36:S72–S87.

Prayogo, C., R. Ratna Sari, D. Harja Asmara, S. Rahayu, and K. Hairiah. 2018. Allometric Equation for Pinang (Areca catechu) Biomass and C Stocks. The Journal of Agricultural Science 40:381-389.

Preece, J., and C. Debuse. Management of Genetic Resources and Associated Information for Grape, Tree Fruit, Tree Nut, and Other Specialty Crops to Mediterranean Climates. USDA; 2014.

Pribyl, D. W. 2010. A critical review of the conventional SOC to SOM conversion factor. Geoderma 156:75–83.

Rabalais, N. N., R. E. Turner, and W. J. Wiseman. 2002. Gulf of Mexico Hypoxia, A.K.A. “The Dead Zone”. Annual Review of Ecology and Systematics 33:235-263.

Raich, J. W., and C. S. Potter. 1995. Global patterns of carbon dioxide emissions from soils. Global Biogeochemical Cycles 9:23-36.

Rutter, P. 2015a. Characteristics of Badgersett hybrid hazels. Date Retrieved: 2018.

Rutter, P. 2015b. What is a "Tubeling"? | Badgersett Research. Date Retrieved: 2018.

Rutter, P. A. 1992. Kill more trees; as fast as possible. Whole Earth Review :110-115.

Rutter, P. A. 1989. Woody Agriculture: Increased Carbon Fixation and Co-production of Food and Fuel. 80th Annual Report of Northern Nut Growers Association.

Rutter, P. A. 1988. Reducing Earth's Greenhouse CO2 Through Shifting Staples Production To Woody Plants. Arbor Day Foundation, From the Proceedings of the Second North American Conference on Preparing for Climate Change.

Rutter, P. A., and M. Shepard. 2002. Hybrid Hazelnut Handbook. :1-36.

Rutter, P. A., S. Wiegrefe, and B. Rutter-Daywater. 2015. Growing Hybrid Hazelnuts: The New Resilient Crop for a Changing Climate. Chelsea Green Publishing.

Sanchez, P. A., R. J. Buresh, and R. R. B. Leakey. 1997. Trees, soils, and food security. Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences 352:949-961.

Schroth, G., M. Souza da Mota, and M. E. de Assis Elias. 2015. Growth and nutrient accumulation of Brazil nut trees (Bertholletia excelsa) in agroforestry at different fertilizer levels. Journal of forestry research 26:347-353.

Seidel, D., S. Fleck, C. Leuschner, and T. Hammett. 2011. Review of ground-based methods to measure the distribution of biomass in forest canopies. Annals of Forest Science 68:225-244.

Smith, J. The History of Temperate Agroforestry. Progressive Farming Trust Limited; 2010. 1 p.

Snare, L. Hazelnut production. PrimeFact 765; 2008 September. 1 p. www.dpi.nsw.gov.

Stringer, L. 2009. Reviewing the links between desertification and food insecurity: from parallel challenges to synergistic solutions. Food Security 1:113-126.

Sullivan, G. T., S. K. Ozman-Sullivan, O. Akbasli, and M. Sahin. 2014. A Tribute to the Hazelnut Plant (Corylus spp.) - the Multiple Uses of Nature's Magnificent Gifts. Acta Horticulturae 1052:371-376.

Szott, L. T., and D. C. L. Kass. 1993. Fertilizers in agroforestry systems. Agroforestry Systems 23:157-176.

TACF. History of the American Chestnut. The American Chestnut Foundation (TACF).

Thomas, S. C., and A. R. Martin. 2012. Carbon Content of Tree Tissues: A Synthesis. Forests 3:332-352.

U.C. Davis FNRI a. Walnut Fact Sheet. University of California, Division of Agriculture and Natural Resources. Fruit & Nut Research & Information (FNRI).

U.C. Davis FNRI b. Almond Nutrients & Fertilization. University of California, Division of Agriculture and Natural Resources. Fruit & Nut Research & Information (FNRI).

U.C. Davis FNRI c. Almond Climate & Cultivars. University of California, Division of Agriculture and Natural Resources. Fruit & Nut Research & Information (FNRI).

U.C. Davis FNRI d. Pecan Processing and Storage. University of California, Division of Agriculture and Natural Resources. Fruit & Nut Research & Information (FNRI).

U.C. Davis FNRI e. Pecan Propagation. University of California, Division of Agriculture and Natural Resources. Fruit & Nut Research & Information (FNRI).

USDA ERS. 2016. U.S. agricultural production occurs in each of the 50 States. United States Department of Agriculture, Economic Research Service (ERS). Last Updated: April 2016.

USDA ERS. 2018a. Fertilizer Use and Price. United States Department of Agriculture, Economic Research Service. Last Updated: February 2018.

USDA ERS. 2018b. Fruit and Tree Nut Yearbook Tables. United States Department of Agriculture, Economic Research Service (ERS). Last Updated: October 2018.

USDA ERS. 2019. Fruit and Tree Nut Overview. United States Department of Agriculture, Economic Research Service (ERS). Last Updated: February 2019.

USDA NASS. 2017a. Walnuts, English - In Shell Production. United States Department of Agriculture, National Agricultural Statistic Service (Quick Stats).

USDA NASS. 2017b. Walnuts, English - Acres Bearing. United States Department of Agriculture, National Agricultural Statistic Service (Quick Stats).

USDA NASS. 2017c. Almonds, Utilized, Shelled - Yield, measured in lbs/acre. United States Department of Agriculture, National Agricultural Statistic Service (Quick Stats).

USDA NASS. 2017d. Hazelnuts - Acres Bearing. United States Department of Agriculture, National Agricultural Statistic Service (Quick Stats).

USDA NASS. 2017e. Almonds, Total Acres Bearing. United States Department of Agriculture, National Agricultural Statistic Service (Quick Stats).

USDA NASS. 2017f. Hazelnuts, Utilized, In Shell - Yield. United States Department of Agriculture, National Agricultural Statistic Service (Quick Stats).

USDA NASS. 2018a. Pecans - Acres Bearing. United States Department of Agriculture, National Agricultural Statistic Service (Quick Stats).

USDA NASS. 2018b. Agricultural Prices. United States Department of Agriculture, National Agricultural Statistic Service (NASS).

USDA NASS. 2018c. Pecans, Utilized, In-Shell - Yield. United States Department of Agriculture, National Agricultural Statistic Service (Quick Stats).

USDA NASS. 2019a. Ohio Corn County Estimates 2018. United States Department of Agriculture, National Agricultural Statistic Service (Quick Stats), Great Lakes Region.

USDA NASS. 2019b. Ohio Soybean County Estimates 2018. United States Department of Agriculture, National Agricultural Statistic Service (Quick Stats), Great Lakes Region.

Valenzuela, H. 2016. Agroecology: A Global Paradigm to Challenge Mainstream Industrial Agriculture. Horticulturae 2:2.

Vazquez, R. I., B. R. Stinner, and D. A. McCartney. 2003. Corn and weed residue decomposition in northeast Ohio organic and conventional dairy farms. Agriculture, Ecosystems and Environment 95:559-565.

Walker, R. E., C. R. Keane, and J. G. Burke. 2010. Disparities and access to healthy food in the United States: A review of food deserts literature. Health and Place 16:876-884.

Weber, C. L., and H. S. Matthews. 2008. Food-miles and the relative climate impacts of food choices in the United States. Environmental science & technology 42:3508–3513.

Williams, N. M., E. E. Crone, T. H. Roulston, R. L. Minckley, L. Packer, and S. G. Potts. 2010. Ecological and life-history traits predict bee species responses to environmental disturbances. Biological Conservation 143:2280-2291.

Wolz, K. J., S. T. Lovell, K. Keeley, R. S. Revord, and E. H. DeLucia. 2017. Frontiers in alley cropping Transformative solutions for temperate agriculture. Global Change Biology 24:883–894.

Woods, J., A. Williams, J. K. Hughes, M. Black, and R. Murphy. 2010. Energy and the food system. Phil. Trans. R. Soc. B 365:2991–3006.

Xu, Y. X., M. A. Hanna, and S. J. Josiah. 2007. Hybrid hazelnut oil characteristics and its potential oleochemical application. Industrial crops and products 26:69-76.

Xu, Y., and M. A. Hanna. 2011. Nutritional and anti-nutritional compositions of defatted Nebraska hybrid hazelnut meal. International Journal of Food Science & Technology 46:2022-2029.

Xu, Y., and M. A. Hanna. 2010. Composition and oxidative stabilities of oils extracted from hybrid hazelnuts grown in Nebraska, USA. International Journal of Food Science & Technology 45:2329-2336.

Youngs, R. L. 2000. A Right Smart Little Jolt: Loss of the Chestnut and a Way of Life. Journal of Forestry.

Zalesny, R. S., J. A. Stanturf, E. S. Gardiner, J. H. Perdue, and T. M. Young. 2016. Ecosystem Services of Woody Crop Production Systems. Bioenergy research 9:465-491.

Zohary, D., and P. Spiegel-Roy. 1975. Beginnings of Fruit Growing in the Old World. Science 187:319-327.

Appendix I

A Brief History of Oberlin's Hazelnut Orchard


June 14th, 2011. Planting of "tubelings" commenced. Heavy clay soil mixed with leaf mulch.


October, 2011. Hazels made little top growth and nearly disappeared under planted clover.

May 23 and August 5th, 2013. In 2 months, hazels more than tripled in size.

June 18th, 2014. The tallest hazelnut tree exceeded 2 meters. For the first time, cluster of nuts appeared on many plants.

August, 2015. First substantial nut harvest occurred 4.5 yrs after planting

July 13th, 2016. 5.5-year-old plants bore a much heavier nut crop. Growth was dense. Initial survival remained at over 90%.

Appendix II

Table 5. Results from 8 ANCOVA tests, each one analyzing a different dependent variable in the experiment, and a TukeyHSD post hoc test. The key is colored to show what is considered significant.

ANCOVAs					
Dependent Variable	Independent Variable	Residuals	Df	F-Value	P-Value
Nut	year	157	1	0.18	0.67
	treatment		2	0.80	0.45
	year:treatment		2	0.31	0.73
Husk	year	157	1	0.91	0.34
	treatment		2	1.06	0.35
	year:treatment		2	0.31	0.74
Repro	year	163	1	0.28	0.60
	treatment		2	2.87	0.06
	year:treatment		2	1.05	0.35
Leaf	year	51	1	43.37	<0.001
	treatment		2	1.01	0.37
	year:treatment		2	0.44	0.65
WoodA	year	108	1	0.24	0.63
	treatment		2	4.36	0.02
	year:treatment		2	1.44	0.24
Struct	year	32	1	1.02	0.32
	treatment		2	1.17	0.32
	year:treatment		2	0.11	0.89
WoodT	year	311	1	1258.5	<0.001
	treatment		2	3.86	0.02
	year:treatment		2	0.93	0.40
SoilT	year	48	1	96.91	<0.001
	treatment		2	2.25	0.12
	year:treatment		2	1.69	0.19
LWARat	year	32	1	19.87	<0.001
	treatment		2	1.78	0.18
	year:treatment		2	0.82	0.45
LWTRat	year	51	1	11.55	<0.001
	treatment		2	0.31	0.73
	year:treatment		2	0.07	0.93
LRRat	year	18	1	4.61	0.05
	treatment		2	0.44	0.65
	year:treatment		2	4.14	0.03
WARRat	year	50	1	0.01	0.93
	treatment		2	0.76	0.47
	year:treatment		2	0.83	0.44

TukeyHSD		
		p adj
Repro	1x-0x	0.227
	1x-2x	0.716
	2x-0x	0.050
WoodA	1x-0x	0.013
	1x-2x	0.730
	2x-0x	0.079
WoodT	1x-0x	0.018
	1x-2x	0.680
	2x-0x	0.109

highly significant	<0.001
significant	<0.05
marginally significant	0.05-0.1
non-significant	>0.1

LWARat = Leaf to WoodA Ratio
LWTRat = Leaf to WoodT Ratio
LRRat = Leaf to Repro Ratio
WARRat = WoodA to Repro Ratio

Table 3. Correlations between variables including the correlation coefficient (R) and the 95% critical value which is determined based on degrees of freedom (https://www.texasgateway.org/resource/126-outliers#eip-idm31993488). If the correlation coefficient is outside the critical value range, then the correlation is significant. Highlighted in green is the only significant correlation.

Correlation	Correlation coefficient (R)	95% Critical Value
repro v woodT	0.0854	0.273
repro v woodA	0.1949	0.304
repro v leaf	0.4156	0.532
woodT v soilT	0.0245	0.273
woodT v LRRat	0.1780	0.273
woodT v NHRat	0.0548	0.273
woodT v leaf	0.8781	0.532
woodA v LRRat	0.5601	0.811
woodA v husk	0.0032	0.304
woodA v soilT	0.0436	0.396
struct v soilT	0.3516	0.632
leaf v soilT	0.5500	0.811
leaf v NHRat	0.6366	0.666

Appendix III

Sampling bias

We must keep in mind that all of the hazelnut trees in this experimental orchard are genetically unique. They have a wide variety of environmental responses and genetic adaptations that may affect biomass samples and relationships. Understanding how an orchard full of these trees functions was a challenge. Like any experiment, our methods were not perfect. For one, different people cycled into data collection based on who was in the Systems Ecology class at that time and who was interested. Dependency on this system created gaps in our data, for example in 2012 and 2016. Sometimes there was just too much work for a small Systems Ecology group to do. With the data that we have, there could be sampling bias due to the variation in people collecting the data. However, specific methodological knowledge was passed from year to year through the detailed reports that the students wrote. Additionally, as the trees grew taller, we needed to alter some methods to be able to take more accurate measurements. For example, we collected leaves by wrapping the hazels in deer netting. Future research groups should experiment with different techniques to make the process less time-intensive.

Appendix IV

In 2011, Sarah M. Bolinger, Charles P. Colwell, Kevin P. DiGuglielmo completed the study, "Urban Woody Agriculture with Hybrid Hazelnuts: A Baseline Study Measuring Tree Biomass and Spatial Heterogeneity in Soil Organic Matter."
In 2013, Eric Xue, Jeremy Gottfried, Alicia Goshe completed the study, "Two annual applications of agricultural fertilizer to two-year-old hybrid hazelnut trees results in significant increase in growth of aboveground woody tissue."
In 2014, Laura Shriver and Yuta Takagi completed the study, "Three years of differential fertilization has no significant effect on the first year of nut production in hybrid hazelnut trees." Additionally, Max Schenk and Olivia Scott completed the study, "Fertilizer Treatment Continues to Affect Woody Biomass in Three-year-old
Hazelnut Trees."
In 2015, Nate Wehr, Arthur Davis, and Geno Arthur completed the study, "Fertilizer application does not affect hazelnut growth in the first significant year of nut production in a hybrid hazelnut orchard."
In 2017, Naomi Fireman and Linnea Halsten completed the study, "Changing Carbon Allocation to Nuts and Woody Tissue in a 7-year-old Experimental Hazelnut Orchard Subjected to Three Levels of Fertilization."
In 2018, Kaitlyn Tonra and Buster Coe completed the study, "Nut, Husk, and Leaf Production as a Function of Age and Fertilization in a Hybrid Hazelnut Orchard." Julie Gerrits, Will Wickham, and Caleb Anderson completed the study, "Developing an allometric equation to estimate woody biomass and the effect of fertilization on biomass accumulation in an experimental hazelnut orchard." Barrett Carr and Amy Sahud completed the study "Impact of Seven Years of Hazelnut Tree Growth and Effects of Three Levels of Fertilizer Treatment on Soil Carbon Sequestration in a Hazelnut Orchard."